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Continuous Air Pollution Source Monitoring Systems

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NOTICE

This is not an official policy and standards document. The opinions, findings, and conclusions are those of the authors and not necessarily those of the Environmental Protection Agency. Every attempt has been made to represent the present state of the art as well as subject areas still under evaluation. Any mention of products or organizations does not constitute endorsement by the United States Environmental Protection Agency.

PREFACE

The emissions standards for stationary sources established by the United States Environmental Protection Agency (EPA) apply to both power and process industries. These standards have forced the development of many methods of emission control over the past decade. In addition, methods to monitor emissions from both controlled and uncontrolled sources have been developed. Included in these monitoring methods is continuous source monitoring instrumentation, which has become sophisticated and reliable enough to provide a determination of the actual level of emissions and a continuous record of the performance of a control device.

The purpose of this handbook is to provide the environmental engineer in industry or in government with a background in continuous monitoring instrumentation. The handbook covers continuous monitoring requirements established by the Federal Government, details of available instrumentation, and methods of using monitor data. The material presented is intended for the engineer who may be familiar with process or control equipment operation but who has had little previous experience with monitoring instrumentation.

The handbook also is intended to serve as a guide for the application of Federal regulations, for the selection of monitoring instrumentation, and for the utilization of monitoring systems for improving and optimizing source process operations. Since the field of instrumentation progresses rapidly, efforts must be made to keep abreast of new developments and to supplement the material in this handbook with information from the current literature.

ABSTRACT

This handbook provides the detailed information necessary to develop a continuous emissions monitoring program at a stationary source facility. Federal and State EPA requirements are given, including design and performance specifications and monitoring and data reporting requirements. Discussions of extractive sampling techniques and in-situ methods are presented, along with explanations of the analytical techniques used in currently marketed instrumentation. Methods for monitoring opacity, pollutant gases, and combustion gases, such as oxygen and carbon dioxide, are described. A detailed explanation of the EPA Performance Specification Test is given along with an explanation of the statistical procedures used to evaluate newly installed systems. Selection procedures for monitoring systems and specific instrumentation are included as a guide to the industrial engineer. Photographs of existing instruments and monitoring systems are presented along with explanatory diagrams to familiarize the reader with the equipment. References are given for each topic discussed in the handbook. The handbook serves as a basic tool for continuous source monitoring, enabling the reader to refer to original research and development work for the initiation of a continuous monitoring program.

CONTENTS

Chapter Page

PREFACE ii

ABSTRACT iv

TABLE OF CONTENTS v

LIST OF FIGURES x

LIST OF TABLES xiii

1 INTRODUCTION 1-1

2 REGULATIONS AND MONITORING REQUIREMENTS 2-1

- 2.1 Introduction 2-1
- 2.2 New Sources – Part 60 2-1
- 2.3 Existing Sources – Part 51 2-6
- 2.4 References 2-9
- 2.5 Bibliography 2-9

3 INTRODUCTION TO THE ANALYTICAL METHODS 3-1

- 3.1 Emission Monitoring 3-1
- 3.2 Monitoring and the Properties of Light 3-2
  - 3.2.1 The Wave Nature of Light 3-3
  - 3.2.2 The Interaction of Light with Matter – Absorption 3-6
  - 3.2.3 The Interaction of Light with Matter – Scattering 3-7
  - 3.2.4 The Interaction of Light with Matter – The Beer-Lambert Law 3-8
- 3.3 References 3-10
- 3.4 Bibliography 3-10

4 CONTINUOUS MONITORS FOR OPACITY MEASUREMENTS 4-1

- 4.1 Opacity and Transmittance 4-1
- 4.2 The Transmissometer 4-2
- 4.3 Design Specifications 4-5
  - 4.3.1 Spectral Response 4-5
  - 4.3.2 Angle of Projection 4-7

CONTENTS–Continued

Chapter

Page

    4.3.3 Angle of View 4-8
    4.3.4 Calibration Error 4-9
    4.3.5 System Response Time Test 4-9
    4.3.6 Sampling Criteria 4-9
    4.3.7 System Operation Check 4-9
  4.4 Installation Specifications 4-10
  4.5 The Performance Specification Test 4-12
  4.6 Data Reporting Requirements 4-13
  4.7 Opacity Monitor Selection 4-17
  4.8 Bibliography 4-17

5 CONTINUOUS MONITORS FOR THE MEASUREMENT OF GASES 5-1

  5.1 Introduction 5-1
  5.2 Extractive Analyzers 5-2
    5.2.1 Extractive Analyzers – Spectroscopic Methods of Analysis 5-3
      5.2.1.1 Nondispersive Infrared Analyzers 5-3
      5.2.1.2 Nondispersive Ultraviolet Analyzers (NDUV) – Differential Absorption 5-8
    5.2.2 Extractive Analyzers – Luminescence Methods of Analysis 5-11
      5.2.2.1 General 5-11
      5.2.2.2 Fluorescence Analyzers for SO_2 5-13
      5.2.2.3 Chemiluminescence Analyzers for NO_x and NO_2 5-16
      5.2.2.4 Flame Photometric Analyzers for Sulfur Compounds 5-18
    5.2.3 Extractive Analyzers – Electroanalytical Methods of Analysis 5-18
      5.2.3.1 General 5-18
      5.2.3.2 Polarographic Analyzers 5-20
      5.2.3.3 Electrocatalytic Analyzers for Oxygen 5-25
      5.2.3.4 Amperometric Analyzers 5-29
      5.2.3.5 Conductimetric Analyzers 5-29
    5.2.4 Extractive Analyzers – Miscellaneous Methods 5-29
      5.2.4.1 Paramagnetic Analyzers for Oxygen 5-29
      5.2.4.2 Thermal Conductivity Analyzers 5-31
  5.3 Bibliography 5-31

CONTENTS–Continued

Chapter | Page

6 EXTRACTIVE SYSTEM DESIGN 6-1

- 6.1 Introduction 6-1
- 6.2 Gas Stream Parameters 6-2
- 6.3 Sampling Site Selection 6-3
  - 6.3.1 SO_2/NO_x Monitors 6-3
  - 6.3.2 O_2/CO_2 Monitors 6-3
  - 6.3.3 General Comments 6-3
- 6.4 Analyzer(s) Selection 6-4
- 6.5 Design of the Sampling Interface 6-4
  - 6.5.1 General 6-4
  - 6.5.2 Sampling Probe 6-5
  - 6.5.3 Coarse Filters 6-5
  - 6.5.4 Fine Filters 6-7
  - 6.5.5 Gas Transport Tubing 6-8
  - 6.5.6 Sampling Pump 6-9
  - 6.5.7 Moisture Removal 6-12
  - 6.5.8 Sampling Interface/Monitor Calibration 6-15
  - 6.5.9 Dilution Systems 6-16
  - 6.5.10 Controlling the Sampling Interface/Monitor System 6-16
- 6.6 Bibliography 6-17

7 IN-SITU MONITORING SYSTEMS 7-1

- 7.1 Introduction 7-1
- 7.2 Terminology 7-1
- 7.3 In-Situ Cross-Stack Analyzers 7-3
  - 7.3.1 Differential Absorption Spectroscopy 7-3
  - 7.3.2 Gas-Filter Correlation Spectroscopy 7-8
  - 7.3.3 Advantages and Limitations 7-11
- 7.4 In-Situ, In-stack Analyzers: Second-Derivative Spectroscopy 7-12
- 7.5 Bibliography 7-20

8 MEASURING, RECORDING, AND REPORTING REQUIREMENTS 8-1

- 8.1 Introduction 8-1
- 8.2 Measuring Requirements 8-2
- 8.3 Recording Requirements and Systems 8-3
  - 8.3.1 Requirements 8-3
  - 8.3.2 Recording Systems – Continuous Analog Recording 8-4

CONTENTS–Continued

Chapter Page

8.3.3 Recording Systems – Intermittent Digital Recording 8-6
8.3.4 Recording Systems – Data Processors 8-7
8.4 Reporting Requirements 8-9
8.5 References 8-16
8.6 Bibliography 8-16

9 EQUIPMENT SELECTION 9-1

9.1 Introduction 9-1
9.2 Vendors of Recording Instrumentation 9-25
9.3 Bibliography 9-28

10 APPLICATIONS OF CONTINUOUS MONITORS 10-1

10.1 Introduction 10-1
10.2 Advantages of Monitoring Data to the Source 10-1
10.3 Advantages of Monitoring Data for the Regulatory Agency 10-2
10.4 Continuous Monitoring: Aid to Manual Source Sampling 10-3
10.5 Bibliography 10-3

11 THE PERFORMANCE SPECIFICATION TESTS 11-1

11.1 Introduction 11-1
11.2 Performance Specification Test 1 – Transmissometer Systems 11-1
11.2.1 General 11-1
11.2.2 Transmissometer Design Criteria 11-1
11.2.3 Performance Specification Test 1 11-3
11.2.4 Zero and Calibration Drift Tests 11-4
11.3 Performance Specification Test 2 – SO_2/NO_x Systems 11-8
11.3.1 General 11-8
11.3.2 Monitor Location and Installation 11-9
11.3.3 Specification Test Procedures 11-10
11.3.4 Calibration Error Test Procedures 11-11
11.3.5 Response Time Test 11-13
11.3.6 Field Relative Accuracy Test 11-14
11.3.7 Instrument Zero Drift and Calibration Drift – 2 Hours and 24 Hours 11-16
11.3.8 The Operational Test Period 11-19
11.4 Performance Specification Test 3 – O_2 or CO_2 Monitors 11-20

CONTENTS–Continued

Chapter Page

11.4.1 Introduction 11-20
11.4.2 Monitor Location and Installation 11-20
11.4.3 O_2 or CO_2 Monitor Calibration Gases 11-21
11.4.4 Instrument Calibration Check 11-21
11.4.5 Response-Time Test 11-22
11.4.6 Zero and Calibration Drift – 2-hour and 24-hour 11-23
11.5 Bibliography 11-24

12 QUALITY ASSURANCE 12-1

12.1 Introduction 12-1
12.2 Calibration Gas Evaluation 12-1
12.3 Instrument Performance Evaluation 12-2
12.4 EPA Inspection Procedures 12-3
12.4.1 Level-One Inspections – (Office Evaluation of Quarterly Reports) 12-3
12.4.2 Level-Two Inspection – (Field Inspection) 12-3
12.4.3 Level-Three Inspection 12-6
12.5 Bibliography 12-7

APPENDIX A – BIBLIOGRAPHY A-1

APPENDIX B – CALCULATIONS FOR THE PERFORMANCE SPECIFICATION TEST B-1

APPENDIX C – F-FACTORS C-1

APPENDIX D – PERFORMANCE SPECIFICATIONS – APPENDIX B TITLE 40 PART 60 – FEDERAL REGISTER D-1

APPENDIX E – CONVERSION FACTORS AND USEFUL INFORMATION E-1

LIST OF FIGURES

Figure No.		Page
3-1	Types of Source Emission Monitors	3-1
3-2	Wavelength	3-3
3-3	The Electromagnetic Spectrum for Continuous Monitoring	3-5
3-4	Light Absorption Processes	3-6
3-5	Light Scattering Effects	3-7
3-6	Light Absorption	3-8
3-7	Calibration Curve for the Beer-Lambert Relation	3-10
4-1	Single-Pass Transmissometer System	4-2
4-2	Double-Pass Transmissometer System	4-3
4-3	Double-Pass Transmissometer Installed at EPA Source Simulator Facility, Research Triangle Park, NC	4-4
4-4	Retroreflector Assembly at the Facility	4-4
4-5	Electromagnetic Spectrum and Factors That Affect Opacity Measurements	4-6
4-6	Particulate Attenuation of Incident Light	4-7
4-7	Angle of Projection	4-8
4-8	Angle of View	4-8
4-9	Lear Siegler RM41-P Showing Instrument "Zero" Reflector	4-10
4-10	Transmissometer Siting	4-11
4-11	Lear Siegler RM41-P Portable Transmissometer	4-12
4-12	Relation Between Emission Opacity at Plume Exit and Monitor Opacity in Duct	4-15
4-13	Two Ducts Entering Common Exit Stack	4-16
5-1	A Lorentzian Absorption Curve	5-3
5-2	Simplified Schematic Diagram of a Nondispersive Infrared Analyzer	5-5
5-3	Operation of the "Microphone" Detector of an NDIR Analyzer	5-5
5-4	Internal View of a Beckman NDIR Analyzer	5-6
5-5	Operation of a "Negative Filter" NDIR Analyzer	5-7
5-6	Internal View of a Bendix NDIR Analyzer	5-8
5-7	The Ultraviolet-Visible Spectrum of SO_2 and NO_2	5-9
5-8	Operation of a Differential Absorption NDUV Analyzer	5-11
5-9	A DuPont NDUV Analyzer at an Industrial Site	5-12
5-10	Internal View of a DuPont Analyzer Showing Measurement Cell and Aspirator	5-12
5-11	Fluorescence Spectrum of SO_2	5-13
5-12	Operation of the SO_2 Fluorescence Analyzer	5-15
5-13	Internal View of a TECO Fluorescence Monitor	5-15

LIST OF FIGURES–Continued

Figure No.		Page
5-14	The Chemiluminescent Emission Spectrum of NO_2	5-16
5-15	Operation of a Chemiluminescence Analyzer	5-17
5-16	Operation of a Flame Photometric Analyzer	5-19
5-17	Instrument Panel of a Meloy Flame Photometric Analyzer	5-20
5-18	Operation of an Electrochemical Transducer	5-21
5-19	Details of the Polarographic Process	5-23
5-20	A Portable Inspection System Using a Polarographic Analyzer	5-24
5-21	An Industrial SO_2 "Alarm" Monitor Using a Polarographic Analyzer	5-25
5-22	Example of a Typical "Concentration" Electrochemical Cell	5-26
5-23	Operation of an Electrocatalytic Oxygen Analyzer	5-27
5-24	A Lear Siegler In-Situ Electrocatalytic Oxygen Analyzer Installed on a Power Plant Stack	5-28
5-25	Operation of a "Magnetic Wind" Paramagnetic Oxygen Analyzer	5-30
6-1	Porous Cylinder Used as External Coarse Filter	6-6
6-2	Actual Porous Cylinder Installed in a Stack Gas Stream	6-6
6-3	Internal Coarse Filter	6-7
6-4	Surface Filter	6-7
6-5	Depth Filter	6-8
6-6	Schematic of Pump Placement – Position A	6-10
6-7	Actual Sampling System with Pump in Position A	6-10
6-8	Schematic of Pump Placement – Position B	6-11
6-9	Actual Sampling System with Position B Pump Location	6-11
6-10	A Refrigerated Chiller Manufactured by Hankinson	6-12
6-11	Interior of Typical Condenser Used for Moisture Removal	6-13
6-12	Schematic Diagram of Permeation Dryer	6-14
6-13	Corrugated Stainless Steel Enclosed Permeation Tube Dryer	6-15
7-1	Types of In-Situ Monitors	7-2
7-2	Operation of In-Situ Differential Absorption Analyzer	7-3
7-3	Mounted EDC Cross-Stack In-Situ Analyzer	7-6
7-4	Internal View of Analytical Section of the EDC Analyzer	7-6
7-5	Internal View of the EDC Light Source Assembly	7-7
7-6	Differential Absorption Spectrometer Installed at Research Triangle Park Source Simulator Facility	7-7
7-7	Operation of a Cross-Stack Gas-Filter Correlation Spectrometer	7-8
7-8	Absorption Principles of a Gas-Filter Correlation Analyzer	7-9
7-9	The Contraves-Goertz Cross-Stack GFC Monitor	7-10
7-10	The Lear Siegler In-Stack In-Situ SO_2-NO Analyzer	7-13

LIST OF FIGURES—Continued

Figure No.		Page
7-11	Second-Derivative Spectrometer Installed and Operating at a Steam Generating Facility	7-13
7-12	Operation of the Second-Derivative In-Stack Monitor	7-14
7-13	Ultraviolet Light Wavelengths Scanned by Spectrometer Moving Mask	7-15
7-14	Scanning a Broad Band Absorption	7-16
7-15	Scanning an Absorption Peak	7-17
7-16	First and Second Derivatives of Linear Absorption	7-18
7-17	First Derivative of an Absorption Curve	7-18
7-18	Second Derivative of an Absorption Curve	7-19
8-1	Possible Methods of Measuring-Recording-Reporting	8-2
8-2	Data from Typical Data Processor Designed for Continuous Source Monitoring Applications	8-8
8-3	Suggested Format for Quarterly Excess Emissions Report	8-12

LIST OF TABLES

Table No. Page

2-1 Industries Required to Monitor Emissions 2-1
2-2 Summary of NSPS Continuous Emission Monitoring Requirements 2-2
2-3 Contents of Part 60 – Appendix B Outline 2-5
2-4 Continuous Monitoring Requirements – Differences Between New and Existing Sources 2-8

3-1 Principles Used in Emission Monitors 3-3

4-1 Opacity Monitor Performance Specifications 4-13

5-1 Infrared Band Centers of Some Common Gases 5-4

8-1 Measuring Requirements 8-2
8-2 Recording Requirements 8-3

9-1 Opacity Monitors – Selection Procedures 9-2
9-2 Gaseous Monitors – Selection Procedures 9-7
9-3 Vendors of Double-Pass Transmissometers 9-12
9-4 Vendors of Single-Pass Transmissometers 9-13
9-5 Principal Continuous Source Monitor Manufacturer Summary (July 1978) 9-14
9-6 Oxygen Analyzer Summary 9-18
9-7 In-Situ Monitor Summary 9-19
9-8 List of Instrument Manufacturers 9-19
9-9 Manufacturers of Strip Chart Recorders 9-26
9-10 Manufacturers of Data Logging Equipment 9-26
9-11 Manufacturers of Continuous Monitor Data Processors 9-27

11-1 Neutral Density Filters for Transmissometer Calibration Error 11-2
11-2 Opacity Monitors Performance Specifications 11-3
11-3 Values for $t_{0.975}$ 11-6
11-4 24-Hour Transmissometer Zero Drift Data 11-7
11-5 Span and Calibration Gas Values 11-9
11-6 Performance Specifications for SO_2/NO_x Systems 11-11
11-7 Performance Specifications for O_2 or CO_2 Monitors 11-20

12-1 Level-Two Inspection Check List 12-4

CHAPTER 1

INTRODUCTION

The application of continuous monitoring techniques to the measurement of pollutants emitted from stationary sources has become an area of growing interest in industry and government. The promulgation of regulations dealing with source level continuous monitors on October 6, 1975, has developed a growing need for information on monitoring systems and their ability to meet the performance specifications defined in the regulations. It is also becoming apparent to personnel in industries affected by the regulations that continuous monitors can save money and improve plant performance in addition to providing continuous source emissions data.

This handbook is intended to provide a background in the field of continuous monitoring to individuals actively engaged in industrial air pollution control programs. Topics in this handbook cover studies ranging from the Code of Federal Regulations to details of instrument operation. A survey is made of presently available instrumentation, and guidelines are given for the selection of monitors. The advantages and limitations of several types of monitoring system designs are reviewed so that the environmental engineer can make informed decisions for a given application.

The performance requirements defined by the Environmental Protection Agency (EPA) and the Code of Federal Regulations for installed monitoring systems are discussed in detail. Siting requirements, drift and calibration limitations, the definition of relative accuracy, and the statistical methods established by EPA for instrument evaluation are all elements of the Performance Specification Test.

It should be kept in mind throughout the reading of this handbook that the intent of the promulgated continuous monitoring regulations was to ensure that a source operator would utilize some type of instrumentation system that could monitor the performance of an air pollution control device. The cost of modern air pollution control equipment is considerable, but all too often, an instrument that could monitor the effectiveness of such equipment is considered unnecessary. However, in many cases modern analytical instruments have been found to increase process efficiency and decrease control equipment operating costs.

Continuous source monitors were not originally intended to be a tool for the enforcement of compliance to the *new source* emission standards (except in the use of primary copper, zinc, and lead smelters – see Ref. 3, Chapter 2). To prove or disprove source compliance, the manual EPA reference methods must still be performed. Several States, however, are developing enforcement programs utilizing continuous monitoring data. Further developments in this regard are expected on the Federal level, as well as from the States.

The technology of source monitoring has advanced rapidly in the past few years along with a steady improvement in instrument reliability. The major concern now is proper application and maintenance. It is the purpose of this handbook to provide a background for selecting and designing an adequate monitoring system for a source application. It is hoped that the guidelines given here will enable those involved in continuous source monitoring to gather reliable, valid emissions data.

CHAPTER 2

REGULATIONS AND MONITORING REQUIREMENTS

2.1 Introduction

Specific source categories are required by law to install and maintain continuous emissions monitoring systems (1)(2)(3). The United States Government publishes the Code of Federal Regulations (CFR) once a year, which is supplemented daily by the Federal Register. It is in these two publications that the regulations concerned with stationary source emissions and emission monitoring may be found. The Federal regulations establish standards and monitoring requirements for new sources. Individual States, however, are required by the Clean Air Act of 1970 to draft regulations for existing sources. It is important that the environmental engineer keep abreast of the CFR and the Federal Register to determine how a facility is to comply with the regulations.

2.2 New Sources – Part 60

Regulations concerning new stationary sources are found under Part 60 of Title 40 of the CFR. Title 40 is composed of five volumes dealing with the protection of the environment. Part 60 deals with the standards of performance for new stationary sources or New Source Performance Standards (NSPS). Table 2-1 gives those source categories required by Part 60 for continuous monitoring of either opacity or some type of gaseous pollutant.

TABLE 2-1

INDUSTRIES REQUIRED TO MONITOR EMISSIONS

Fossil-Fuel-Fired Steam Generators	Sulfuric Acid Plants
Nitric Acid Plants	Petroleum Refineries
Primary Copper Smelters	Iron and Steel Plants
Primary Zinc Smelters	Ferroalloy Production Facilities
Primary Lead Smelters	Kraft Pulp Mills

The Federal Register published on October 6, 1975, is the document in which the EPA performance specifications for continuous monitoring systems were promulgated. Several minor points have been revised by subsequent publication in the Federal Register, but pages 46250 to 46271 of the October 6, 1975 document, cover the agency's position on continuous monitors for new sources. Limits of drift and acceptable error limits for monitors are given; but more importantly, the October 6, 1975, Federal Register establishes the position that the EPA *does not approve* specific brands of instrumentation or specific analytical methods (in the case of gas monitoring) for source monitoring systems. This is in contrast to the policy of approving specific instrument models for continuous *ambient* air analysis. What has been established, however, is the Performance Specification Test. EPA provides latitude in continuous monitoring system design and application to allow sources to handle individual problems. The installed system must prove that it meets specified, minimum requirements for instrument location, drift, accuracy, etc. These points will be covered in subsequent chapters of this handbook.

Table 2-1 gives the source categories required to install some type of monitoring system. The primary question deals with what is to be monitored. A partial listing is given in the October 6, 1975, document. A complete summary of the requirements for a given category is given in the CFR. As stated previously, the NSPS come under Part 60 of Title 40 of the CFR. Each source category that is currently regulated under these standards is assigned a subpart letter. For example, sulfuric acid plants come under Subpart H. A summary of the emission parameters required to be monitored, emission limits, and applicability dates for each new source category is given in Table 2-2.

TABLE 2-2

SUMMARY OF NSPS CONTINUOUS
EMISSION MONITORING REQUIREMENTS

Source Category	Affected Facility	Monitoring Required	Emissions Standards	Averaging Time
Fossil-fuel-fired steam generators (Subpart D) >73 megawatts heat input rate August 17, 1971	Coal-fired boilers	Opacity	20%	6 minutes
		SO_2	520 nanograms/joule (1.2 lb/10^6 Btu)	3 hours
		NO_x (only if emissions >70% of standard)	300 nanograms/joule (0.70 lb/10^6 Btu)	3 hours
		O_2 or CO_2 for conversion factors		
	Oil-fired boilers	Opacity	20%	6 minutes
		SO_2	340 nanograms/joule (0.20 lb/10^6 Btu)	3 hours
		NO_x	130 nanograms/joule (0.30 lb/10^6 Btu)	3 hours
		O_2 or CO_2 for conversion factors		

TABLE 2-2

SUMMARY OF NSPS CONTINUOUS EMISSION MONITORING REQUIREMENTS—Continued

Source Category	Affected Facility	Monitoring Required	Emissions Standards	Averaging Time
	Gas-fired boilers	NO_x (only if emissions >70% of standard)	86 nanograms/joule (0.20 lb/10^6 Btu)	3 hours
		O_2 or CO_2 for conversion factors		
Nitric acid plant (Subpart G) August 17, 1971	Process equipment	NO_x	1.5 kg/metric ton of acid produced (3.0 lb/ton)	3 hours
Sulfuric acid plant (Subpart H) August 17, 1971	Process equipment	SO_2	2.0 kg/metric ton of acid produced (4 lb/ton)	3 hours
Petroleum refineries (Subpart J) June 11, 1973	FCC catalyst regenerator	Opacity	30% except one 6 min. period/hr.	6 minutes
		Carbon monoxide	0.050% by volume	1 hour
	Fuel gas combustion device	H_2S	230 mg/dscm 0.1 gr/dscf)	3 hours
	Claus recovery units oxidation on reduction control systems followed by an incinerator	SO_2	0.025% by volume at 0% O_2 on a dry basis	12 hours
	Reduction control system without an incinerator	Reduced sulfur compounds	0.030% by volume at 0% O_2 on a dry basis	12 hours
		H_2S calculated as SO_2	0.0010% by volume at 0% O_2 on a dry basis	12 hours

TABLE 2-2

SUMMARY OF NSPS CONTINUOUS EMISSION MONITORING REQUIREMENTS–Continued

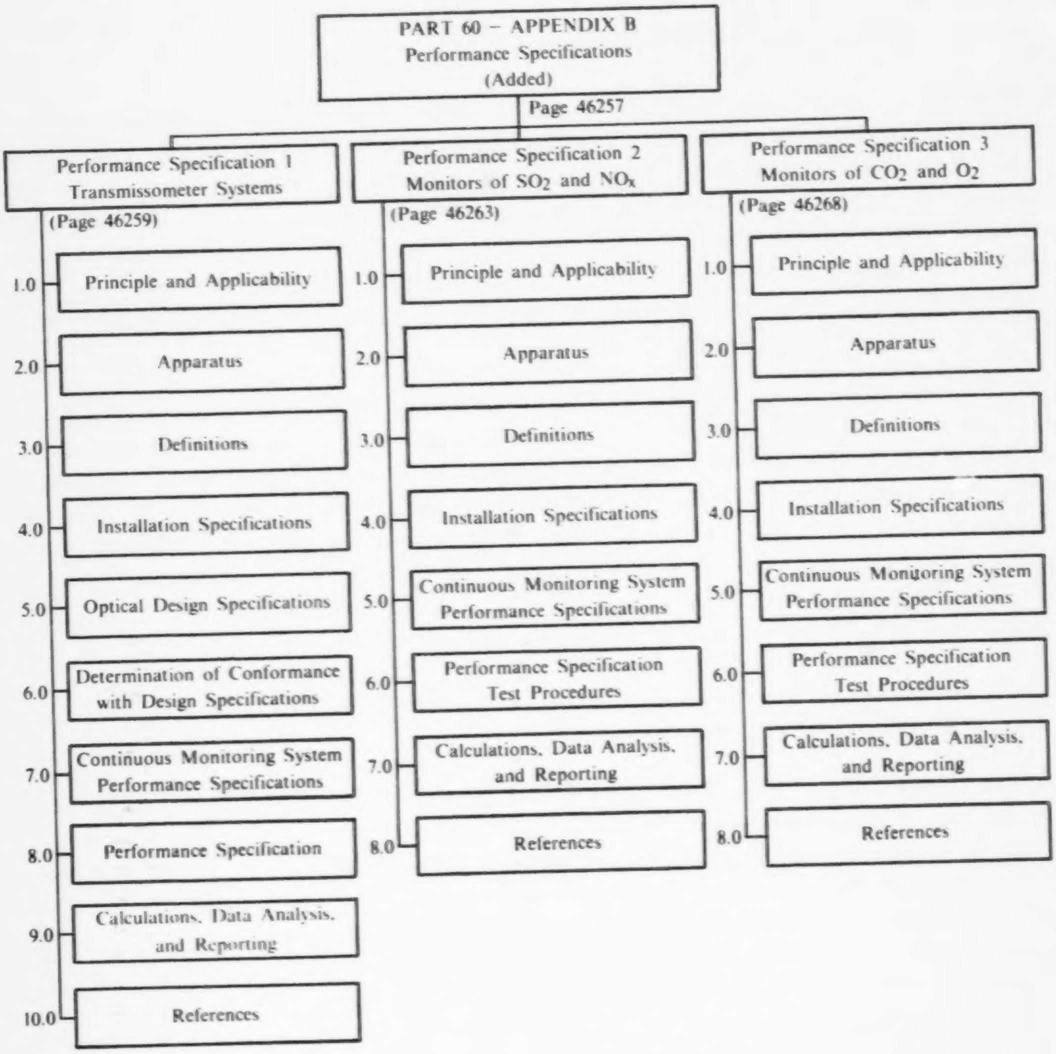
Source Category	Affected Facility	Monitoring Required	Emission Standards	Averaging Time
Primary copper smelters (Subpart P) October 16, 1974	Dryer	Opacity	20%	6 minutes
	Roaster, smelting furnace on copper converter	SO_2	0.065% by volume	6 hours
Primary zinc smelters (Subpart Q) October 16, 1974	Sintering machine	Opacity	20%	6 minutes
	Roaster	SO_2	0.065% by volume	2 hours
Ferroalloy production facility (Subpart Z) October 21, 1974	Electric submerged arc furnace	Opacity	15%	6 minutes
Iron and steel plants (Subpart AA) October 24, 1974	Electric arc furnace control device	Opacity	3%	6 minutes
Kraft pulp mills (Subpart BB) February 23, 1978	Recovery furnace	Opacity	35%	6 minutes
	Any and all process equipment (exceptions noted in 43 FR 7568 2/23/78)	Total reduced sulfur (TRS)	5 ppm corrected to 10% oxygen	12 hours
		Oxygen		12 hours

Once it has been determined that a continuous monitoring system is required for measuring opacity or the concentration of a specific gas, the type of system or instrument that will best satisfy the EPA performance specifications and the needs of the plant must be selected. The performance specifications give the general characteristics expected of an instrument and clearly define procedures for checking the installed instrument performance. These methods are given in Appendix B of Part 60 of the CFR and are also included in the appendix of this handbook. An outline of the contents of Appendix B is given in Table 2-3.

From Table 2-3, it can be seen that, at present, there are performance specifications for opacity monitors (transmissometers), SO_2 and NO_x monitors, and CO_2 and O_2 monitors. Each specification discusses the installation requirements, the levels of performance expected of the instrument system over a 1-week operational test period, and the statistical methods of analyzing the data obtained over the test period. The specifications for opacity monitors include a number of design characteristics such an instrument must possess. Design specifications are not given for the gaseous analyzers.

TABLE 2-3

CONTENTS OF PART 60 – APPENDIX B OUTLINE


PART 60 – APPENDIX B
Performance Specifications
(Added)
Page 46257
Performance Specification 1
Transmissometer Systems
(Page 46259)
1.0 Principle and Applicability
2.0 Apparatus
3.0 Definitions
4.0 Installation Specifications
5.0 Optical Design Specifications
6.0 Determination of Conformance with Design Specifications
7.0 Continuous Monitoring System Performance Specifications
8.0 Performance Specification
9.0 Calculations, Data Analysis, and Reporting
10.0 References
Performance Specification 2
Monitors of SO2 and NOx
(Page 46263)
1.0 Principle and Applicability
2.0 Apparatus
3.0 Definitions
4.0 Installation Specifications
5.0 Continuous Monitoring System Performance Specifications
6.0 Performance Specification Test Procedures
7.0 Calculations, Data Analysis, and Reporting
8.0 References
Performance Specification 3
Monitors of CO2 and O2
(Page 46268)
1.0 Principle and Applicability
2.0 Apparatus
3.0 Definitions
4.0 Installation Specifications
5.0 Continuous Monitoring System Performance Specifications
6.0 Performance Specification Test Procedures
7.0 Calculations, Data Analysis, and Reporting
8.0 References

In summary, Part 60 of the CFR incorporates the requirements for the continuous monitoring of designated *new* stationary sources. The manner in which continuous monitoring systems are expected to perform after being installed on a source is given in Appendix B of Part 60. Existing sources are regulated by the States, and the continuous monitoring requirements for existing sources must be established by each State.

2.3 Existing Sources – Part 51

Since existing sources far outnumber new sources, continuous monitoring requirements for existing sources have a greater impact on an entire industry. There is a significant difference, however, between regulations for new and existing sources. As part of the Clean Air Act, the States must regulate existing sources. The Federal Government regulates new sources. The States, however, may not arbitrarily set standards and regulations. They must follow certain minimum requirements established by EPA.

The Federal requirements that each State must follow when drafting regulations for continuous source emission monitors are found in Part 51 of Title 40 of the CFR (4). Regulations and specifications are given for new sources in Part 60, but only requirements for the preparation, adoption, and submittal of State regulations are given in Part 51. Once the State regulations are approved by EPA, they become part of the State Implementation Plan (SIP). The SIP is a continually evolving document that establishes the procedures through which a State plans to meet the ambient air quality standards set by EPA and other goals established by the Clean Air Act.

The Federal requirements for individual State continuous emission monitoring regulations are given in Appendix P of Part 51. The requirements were published in the October 6, 1975, Federal Register at which time, 1 year was given for the States to submit continuous emissions monitoring regulations as part of their SIP's. No State met that deadline; however, most States have either submitted some regulations or are actively developing them. The date when these regulations are approved is important to the affected industries. Each existing source that is required to install continuous monitoring systems must do so within 18 months from the date of approval. Regulated industries must be aware of and meet this deadline. There are presently four source categories for which States must draft continuous monitoring regulations: fossil-fuel-fired steam generators, sulfuric and nitric acid plants, and petroleum refineries.

Several exemptions are allowed for existing sources which do not arise for sources covered by the New Source Performance Standards. The exemptions were allowed so that undue hardship would not be placed on existing facilities or on those that will be retired within 5 years (5 years after inclusion of the source category in Part 51 Appendix P). Also, States are only required by EPA to monitor sources that have an emission standard for SO_2, NO_x, or opacity in its SIP for that source category. The aim in Part 51 is to have States develop regulations that will be fair to existing sources. Sulfuric acid and nitric acid plants would be required to install monitors if they have production capacities greater than 300 tons per day. Catalyst regenerators at petroleum refineries need to monitor opacity only if they have a feed capacity of greater than 20,000 barrels per day.

In contrast to new fossil-fuel-fired steam generators that burn oil or coal, existing fossil-fuel-fired plants will be required by the States to monitor SO_2 emissions only if a flue gas desulfurization (FGD) system is used. EPA, however, is currently considering extending SO_2 monitoring to existing sources that do not have FGD systems. Also, for existing plants, NO_x emissions are to be continuously monitored if the plant is within an Air Quality Control Region (AQCR) that has a control strategy for nitrogen oxides, if the source has a heat input rate of greater than 1000×10^6 Btu/hr, and if the source emits nitrogen oxides at levels greater than 70 percent of the State NO_x standard. A summary of the differences for monitoring requirements between new and existing sources is given in Table 2-4.

Once it has been established that an existing source must install a continuous monitoring system, the instrument specifications, the data reporting requirements, and the Performance Specification Test Requirements are the same as those for new sources. In fact, in Part 51, which gives the minimum requirements for the State regulations, it is stated that each State plan must incorporate, as a minimum, the contents of Appendix B Part 60 (which gives the Performance Specifications for monitoring systems on new sources, as discussed earlier). Existing sources may have continuous monitors already in use which may not meet the EPA Performance Specifications of Appendix B. This case is covered by a grandfather clause that requires monitors installed before September 11, 1974, to demonstrate an accuracy of only ±20 percent with respect to the reference method. These older monitors are to undergo a complete Performance Specification Test 5 years after approval of the SIP continuous monitoring regulations.

The States are allowed some degree of latitude on a case-by-case basis in making exceptions or in permitting alternative monitoring requirements for an existing source. Examples of special cases would be the presence of condensed water in the flue gas stream, infrequent operation of a facility, or difficulties in installing a continuous monitoring system because of physical limitations at the facility.

In summary, the intentions of requirements of Part 51 are that the continuous monitoring regulations of the States satisfy the following points:

- Allow the utilization of existing instrumentation where possible.
- Reduce installation costs where possible.
- Reduce maintenance costs where possible.
- Reduce the number of monitors required where possible.
- Encourage new technology.

TABLE 2-4

CONTINUOUS MONITORING REQUIREMENTS – DIFFERENCES BETWEEN NEW AND EXISTING SOURCES

Source Category	Pollutant	New Sources	Existing Sources
Fossil-fuel-fired steam generators	Opacity SO_2	>250 million Btu/hr	>250 million Btu/hr SO_2 only if flue gas desulfurization used and >30% capacity factor
	NO_x	>250 million Btu/hr and if emissions >70% of standard	NO_x only where control strategy required and if >70% of standard and if $>1000 \times 10^6$ Btu/hr heat input
	O_2 or CO_2	(If SO_2 or NO_x monitor required)	O_2/CO_2 only if State requires data for converting to emissions standard
Sulfuric acid plants	SO_2	All sources covered by NSPS	>300 ton/day production
Nitric acid plants	NO_2	All sources covered by NSPS	>300 ton/day production and only where control strategy required
Petroleum refineries – catalyst regenerators for fluid bed catalytic cracking units	Opacity	All sources covered by NSPS	>20,000 bbl/day
Electric arc furnaces	Opacity	All sources covered by NSPS	Possible future requirements
Primary copper, zinc, and lead smelters	Opacity SO_2	All sources covered by NSPS	Possible future requirements
Ferroalloy production facilities	Opacity	All sources covered by NSPS	Possible future requirements
Kraft pulp mills	Opacity TRS O_2	All sources covered by NSPS	Possible future requirements
Portland cement kilns and cylinder coolers	Opacity	Possible future requirements	Possible future requirements

2.4 References

1. U.S. EPA, "Standards of Performance for New Stationary Sources," Code of Federal Regulations, 40 CFR, Part 60.

2. U.S. EPA, "Requirements for Submittal of Implementation Plans Standards for New Stationary Sources – Emission Monitoring," Federal Register 40, FR 46240–46271, October 6, 1975, and Revisions:

   41 FR 44838, 10/12/75, "Approval of Alternate Monitoring Requirements" (Definition of the Wet F Factor).

   42 FR 5936, 1/3/77 " Revision to Emission Monitoring Requirements and to Reference Methods" (Use of CO_2 Monitors, After Wet Scrubbers, Clarification of Data Recording Requirements for Opacity Monitors, Other Clarifications).

   42 FR 26502, 5/23/77 "Compliance with Standards and Maintenance Requirements" (Use of Continuous Monitoring Data as Evidence).

3. U.S. EPA, "Continuous Monitors and Primary Smelters – Use in the Compliance Test," 41 FR 2338 see 60.166a2.

4. U.S. EPA, "Requirements for Preparation, Adoption, and Submittal of Implementation Plans," Code of Federal Regulations, 40 CFR, Part 51.

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U.S. EPA, *Compliance Status of: Major Air Pollution Facilities* — Stationary Source Enforcement Series EPA-340/1-76-010, December 1976.

U.S. EPA, *Standards of Performance for New Stationary Sources — A Compilation as of August 1976*, EPA-340/1-76-009, August 1976.

U.S. EPA, *Conference Report and Responses to Key Questions and Issues*, Continuous Emissions Monitoring Conference, Dallas, Texas, February 15-17, 1978, EPA-340 1-77-025, Stationary Source Enforcement Series, December 1977.

CHAPTER 3

INTRODUCTION TO THE ANALYTICAL METHODS

3.1 Emission Monitoring

Federal or State regulations will dictate whether an opacity monitor, gas monitors, or both are required on a given source. Many sources will be required to monitor opacity only. In such cases, instrument selection is relatively easy, since there is only one measurement principle that will satisfy the EPA opacity monitor design specifications. On the other hand, selection of gas monitors is more difficult, since EPA has established no design specifications in this case. A gaseous emission monitor can be approved if it performs according to EPA specifications once it is installed on the source. Any chemical or physical monitoring method can be used so long as it accurately monitors emissions (accurate, relative to the reference methods for determining pollutant gas concentration, being defined in 40 CFR Part 60 Appendix B).

There are many instruments marketed for monitoring emissions from stationary sources. Opacity monitors may be either single-pass or double-pass systems (these will be discussed in Chapter 7). Gas monitoring systems may be either extractive systems, in-situ systems, or remote monitoring systems. These divisions are shown in Figure 3-1.

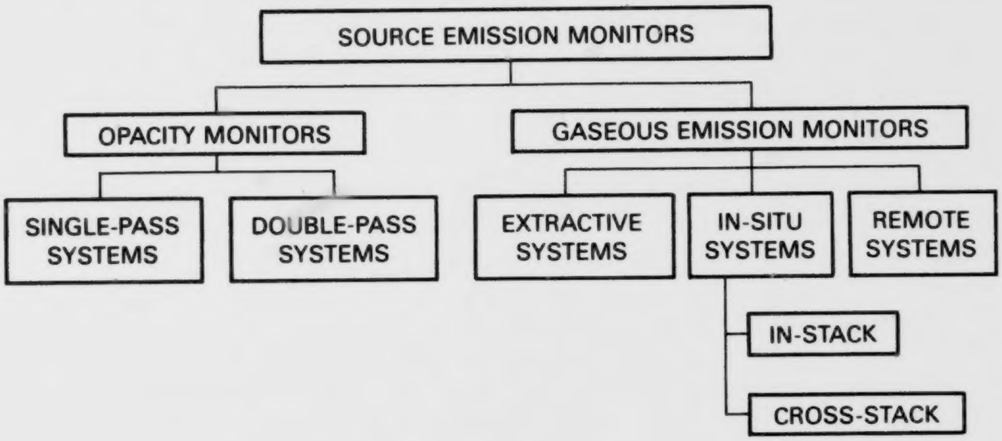

SOURCE EMISSION MONITORS
OPACITY MONITORS
GASEOUS EMISSION MONITORS
SINGLE-PASS SYSTEMS
DOUBLE-PASS SYSTEMS
EXTRACTIVE SYSTEMS
IN-SITU SYSTEMS
REMOTE SYSTEMS
IN-STACK
CROSS-STACK

FIGURE 3-1

TYPES OF SOURCE EMISSION MONITORS

Extractive gas monitors were the first type of instruments to be incorporated into continuous gas monitoring systems. Many of the first extractive systems used modified ambient air analyzers, or they adapted an ambient air analyzer to source applications with the use of a gas dilution system. Many problems were found with this type of approach. Systems were later designed to deal directly with the problems of extracting, sampling, and analyzing pollutant gases at source level concentrations.

The in-situ gaseous emission analyzers are the second generation of instruments designed for source monitoring. The analysis is performed on the gas as it exists in the stack or duct (hence, in-situ) generally by some advanced spectroscopic technique. These analyzers are installed either across a stack (cross-stack) or employ a probe inserted into the flue gas stream (in-stack). These two types of in-situ analyzers do not extract or modify the flue gas.

The remote monitoring instrument is the third and latest generation of the source monitoring techniques. These instruments use laser and other spectroscopic methods to monitor emissions at distances from 500 to 1000 meters away from the source. At the present time, remote systems are used by government agencies and their contractors for research into specific emission problems. Performance specifications have not been written for remote monitoring systems, but such systems soon may find some utility in enforcement cases. Reference 2 of this chapter provides an excellent overview of remote sensing techniques.

The analytical techniques used in continuous source monitors encompass a wide range of chemical and physical methods. These vary in range from chemical methods as basic as coulometric titration to the measurement of light produced in a chemiluminescent reaction. Principles of physics as basic as light scattering are utilized as are the more complicated methods of detecting light absorption by second-derivative spectroscopy. A summary of the principles of chemical physics that are used in currently marketed emission monitoring systems is given in Table 3-1.

Before each of these methods is discussed in detail, it is necessary to review some basic principles of chemical physics. In the next section, the characteristics of the interaction of light with particulates and gases will be discussed.

3.2 Monitoring and the Properties of Light

The majority of instruments developed for continuous emission monitoring utilize some phenomenon arising from the interaction of light with matter. Opacity monitors measure the effects of light scattering and absorption; a nondispersive infrared analyzer measures the amount of light absorbed by a pollutant molecule; and a chemiluminescence analyzer senses the light emitted in a chemical reaction. A better understanding of the details of instrument operations can be gained by reviewing some of the properties of light and by examining the nature of light scattering and absorption.

TABLE 3-1

PRINCIPLES USED IN EMISSION MONITORS

	Gaseous Emission Monitors	
Opacity Monitors	Extractive Systems	In-Situ Systems
Visible light scattering and absorption	*Absorption Spectroscopy* Nondispersive infrared Differential absorption *Luminescence Methods* Chemiluminescence (NO_x) Fluorescence (SO_2) Flame photometry *Electroanalytical Methods* Polarography Electrocatalysis (O_2) Amperometric Analysis Conductivity Paramagnetism (O_2)	*Cross-Stack* Differential absorption Gas-filter correlation *In-Stack* Second-derivative spectroscopy Electrocatalysis (O_2)

Note: (Methods followed by the gas in parenthesis indicate that the technique is currently commercially applied only to that gas)

3.2.1 The Wave Nature of Light

Light has a wave nature; it is composed of oscillating electric and magnetic fields. Light waves, or electromagnetic waves as they are better termed, are characterized by their wavelength or frequency. Figure 3-2 shows a typical oscillating electric field as a function of distance at a frozen instant in time.

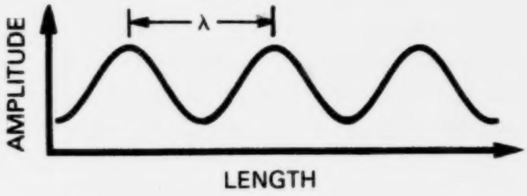


FIGURE 3-2

WAVELENGTH

The length between successive oscillations of a wave is called the wavelength (λ). The period of time that it takes a wave to go through an oscillation cycle is called the frequency (υ). Since light waves travel at a speed, $c = 3 \times 10^{10}$ cm/sec, the following relationship exists between wavelength and frequency:

$$\text{Frequency} = \frac{\text{speed of light}}{\text{wavelength}}$$

$$\upsilon = \frac{c}{\lambda} \qquad \frac{\text{cm/sec}}{\text{cm}} = 1/\text{sec (cycle/second)}$$

Literature describing continuous monitoring instruments often uses wavelength to characterize the spectral region of light that is used in the analytical method. Another term often used for the same purpose is the wavenumber. The wavenumber is expressed as:

$$\bar{\upsilon} = \frac{c/\lambda}{c} = \frac{1}{\lambda}$$

(1/cm or cm^{-1}: the number of wavelengths per centimeter)

The units of $\bar{\upsilon}$ are those of cm^{-1}, called reciprocal centimeters or wavenumbers. The wavenumber, $\bar{\upsilon}$, is essentially a measure of frequency, differing from υ by the constant factor of the velocity of light.

The light used in continuous monitoring instrumentation ranges from ultraviolet light, with a wavelength of 200 nanometers, to infrared light, with a wavelength of 6000 nanometers. Figure 3-3 shows the regions of the electromagnetic spectrum used in continuous monitoring methods.

It should be noted that different spectral regions often use different units for the expression of wavelength. For example, angstroms have historically been used in the ultraviolet to identify wavelengths, whereas in the infrared, micrometers and wavenumbers are commonly used by spectroscopists. This difference in units arose from the independent development of each field of spectroscopy. Different unit scales have been placed on Figure 3-3 for easy reference. It should be noted that in the ultraviolet and visible region, angstroms and nanometers are most commonly used (1 nm = 10 angstrom = 10^{-9} meter; see Appendix E). In the infrared, micrometers (μm) tend to be used interchangeably with reciprocal centimeters (wavenumbers) when characterizing light. To change between the two designations, obtain the reciprocal of the wavelength expressed in μm and multiply by 10^4 to obtain wavenumbers in units of cm^{-1}.

For example, if

$$\lambda = 5\ \mu\text{m} \qquad 1/\lambda = \frac{1}{5\ \mu\text{m}} \times 10^4 \frac{\mu\text{m}}{\text{cm}} = 2000\ \text{cm}^{-1}$$

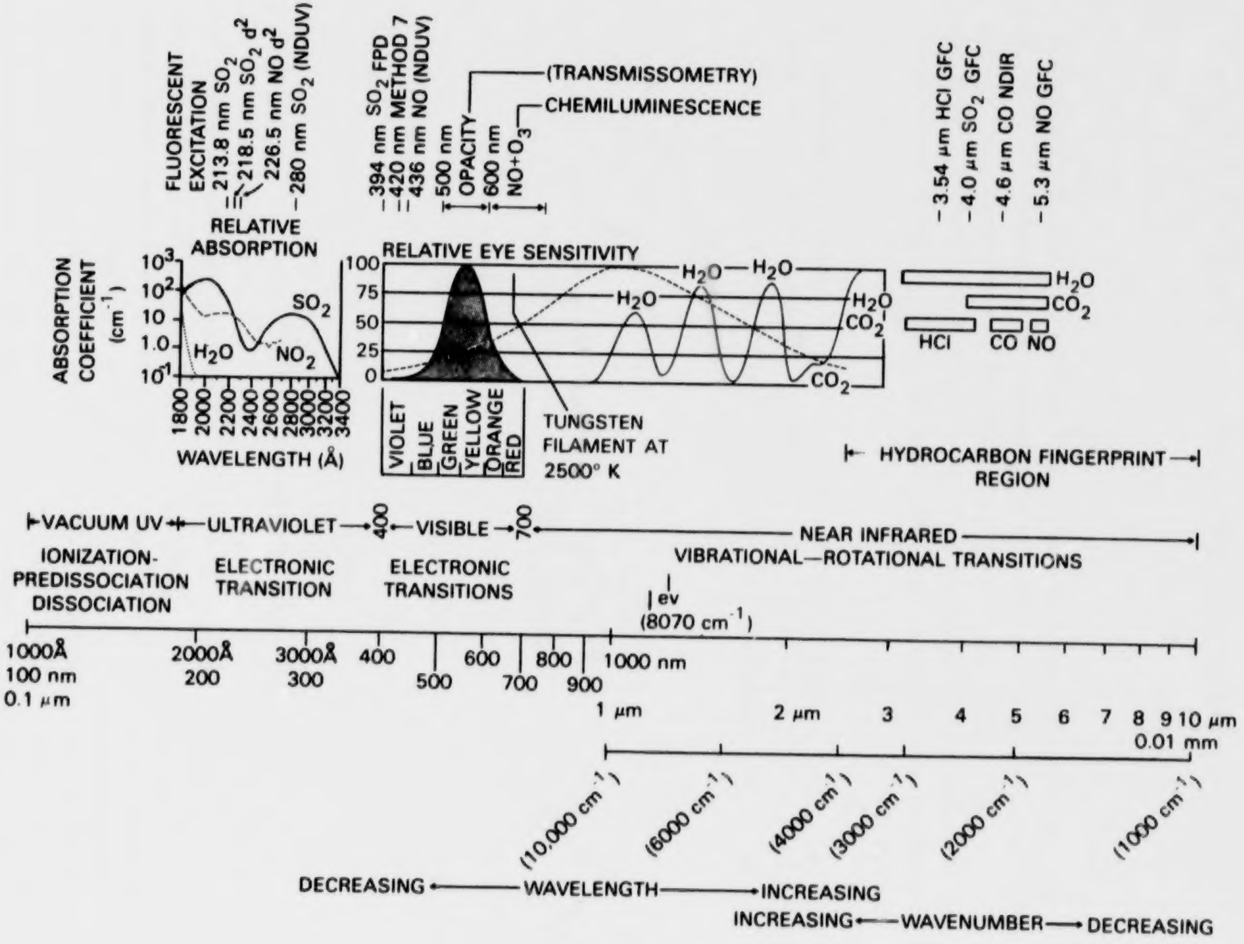


FIGURE 3-3

THE ELECTROMAGNETIC SPECTRUM FOR CONTINUOUS MONITORING

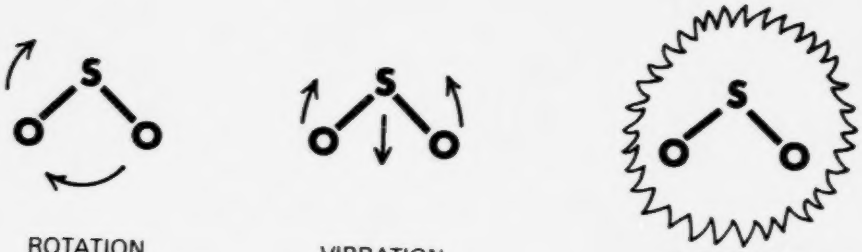
3.2.2 The Interaction of Light with Matter – Absorption

Light carries energy. This is obvious to anyone who has sat on a beach and absorbed the rays of the sun. Early in this century, Max Planck deduced that parcels of light (photons) carry energy according to the relation:

$$\Delta\epsilon = h\upsilon = \frac{hc}{\lambda}$$

where $\Delta\epsilon$ is the amount of energy, and h is Planck's constant. This expresses the fact that light of shorter wavelengths (e.g., light in the ultraviolet) will carry with it more energy than light of longer wavelengths (e.g., light in the infrared). In monitoring instruments, therefore, light of different wavelengths will have different effects on a pollutant molecule. This is an important point to realize, especially when the effects of interfering molecules need to be considered.

Molecules are made up of atoms, and an atom is made up of a nucleus and electrons. If light energy strikes a molecule, the atoms and electrons can do certain things, if the energy is of the right value. For example, refer to Figure 3-4 for the SO_2 molecule.



ROTATION
(a)

VIBRATION
(b)

ELECTRONIC
(c)

FIGURE 3-4

LIGHT ABSORPTION PROCESSES

Light of low energy (long wavelength) will cause a molecule to rotate as shown in Figure 3-4a. Light of somewhat higher energy may cause the atoms to move back and forth in one of the normal modes of vibration of the molecule as shown in Figure 3-4b. Light having the correct wavelength in the ultraviolet region of the electromagnetic spectrum may have enough energy to excite an electron in the molecule and make it jump into a new orbit. This is an electronic transition. The science of chemical physics has shown that the energy must be exactly the right value to cause a rotational, vibrational, or electronic transition. When one of these excitations does occur, the light is said to be absorbed. In absorption, energy has been lost from the light beam and has been transferred to the molecule.

In Figure 3-3, the electromagnetic spectrum for continuous monitors shows the regions of the spectrum in which molecules absorb light energy. In the infrared and near-infrared region, rotational transitions occur at the longer wavelengths, and vibrational transitions occur at the shorter wavelengths (higher energy). Generally, the vibrations of the molecule will be coupled with the rotations to produce distinct absorption spectra. There are CO, CO_2, NO, and SO_2 monitors that operate in the region of 3 to 6 μm, based upon the excitation of vibrational-rotational energy states by the absorption of infrared light.

In the visible and ultraviolet region of the electromagnetic spectrum, electronic transitions occur where the electrons in the pollutant molecules become excited and jump into a new energy state because of the impinging light. The technology associated with the measurement of ultraviolet light is quite advanced, and in the region of 200 nm there are few interfering species. As a result, a number of monitors have been developed to measure SO_2 in this region of the ultraviolet range.

3.2.3 The Interaction of Light with Matter – Scattering

There is another way to remove energy from a beam of light other than by absorption. Light can be scattered in different directions if it impinges upon aerosols or particulates. The mechanism of light scattering is somewhat complex, but the details become important when monitoring the opacity of a flue gas.

Depending upon the size of a particle, light scattering can be described in macroscopic or microscopic terms. For large particles, where the wavelength of light is smaller than the size of the particle (0.5 μm for the wavelength and 1.0 μm or greater for the particle), the macroscopic phenomena of reflection, refraction, and diffraction describe the scattering process. Figure 3-5 shows these effects.

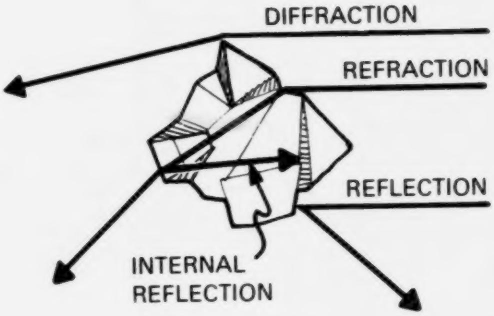


FIGURE 3-5

LIGHT SCATTERING EFFECTS

- Reflection is a change in the direction of light after striking the surface of a particle.

- Refraction occurs after light enters the particle; its speed and direction change because of the optical characteristics (refractive index) of the material. Once light has entered the particle, it can also undergo internal reflection.

- Diffraction is a bending of light around an object caused by the interference of light waves near the surface of the object.

For visible light and particles having a size near 1 μm or larger, the light will be primarily scattered in the forward direction. The transmission of light through a plume containing many particles will be reduced, because the light will scatter before emerging from the plume.

Particles smaller than about 0.1 μm will scatter visible light by a process called dipole or Rayleigh scattering. In this case, the light interacts with the electrons, oscillating them in the electromagnetic field. An accelerating electron will emit electromagnetic radiation (in virtually all directions) at the same frequency at which it is oscillating. This is dipole scattering; visible light interacts with the small particle and is scattered equally forward and backward. As a result of this phenomenon, small particles are very effective in scattering light. This phenomenon is important when studying the transmission of light through a flue gas.

3.2.4 The Interaction of Light with Matter – The Beer-Lambert Law

The continuous emission monitors that utilize light in the measurement process apply the Beer-Lambert law. (Consider Figure 3-6.)

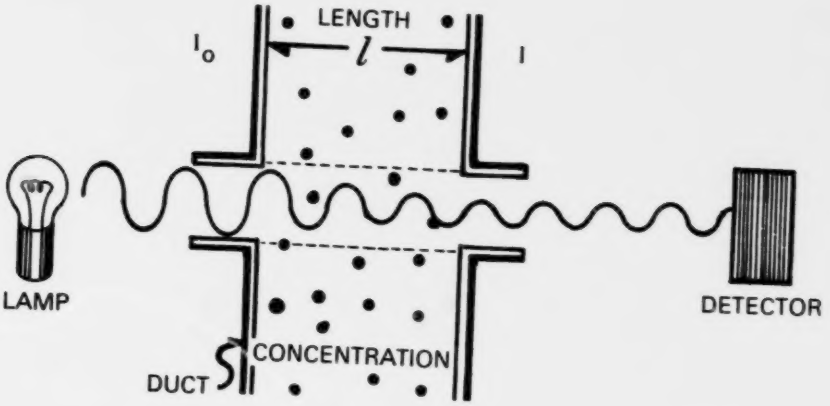


FIGURE 3-6

LIGHT ABSORPTION

The Beer-Lambert law states that the transmittance of light through a medium that absorbs or scatters light is decreased exponentially by the product $\alpha c l$, or

$$T = I/I_o = e^{-\alpha c l}$$

where:

T = transmittance of light through the flue gas

I_o = intensity of the light energy entering the gas

I = intensity of the light energy leaving the gas

α = attenuation coefficient

c = concentration of the pollutant

l = distance the light beam travels through the flue gas.

The attenuation coefficient, α, is dependent upon the wavelength of the radiation and also upon the properties of the molecule or particle. In the case of particulates, α characterizes the effects of scattering and absorption. The coefficient tells how much a molecule will absorb light energy at a given wavelength. If no absorption occurs, α will be zero, and the transmittance would equal 100 percent. If an electronic or vibrational-rotational transition occurs at some wavelength, α will be a large number, and the reduction of light energy across the path l will depend upon the pollutant concentration, c, and the original intensity, I_o, of the light beam.

Utilizing this principle, an instrument for determining the concentration of a pollutant in a flue gas can be designed. All that is needed is light having a wavelength that will cause a transition in the molecule of interest and a light detector. I_o is determined by taking a reading from the detector when no pollutant is in the duct or sample cell. The concentration is obtained from the Beer-Lambert law if α and l are known. Generally, a calibration curve is generated with known gas concentrations rather than using a theoretical value for α (see Figure 3-7).

The complexity of modern monitoring instrumentation arises from the need to analyze one specific pollutant in a sample containing many types of gases. The cross-stack and in-stack gas monitors must also be designed to eliminate the effects of particulate matter in reducing the light transmission. There are, of course, problems in choosing and designing light sources, detectors, and optical assemblies, as well as with the electronic circuitry. The ability of an instrument manufacturer to solve the problems of specificity and design are reflected in the operation of the monitor itself.

The approaches which instrument companies have taken in designing source level pollutant monitors will be discussed in detail in the next two chapters. Opacity monitors, compared to the gaseous emission monitors, are relatively simple and will be discussed in Chapter 4.

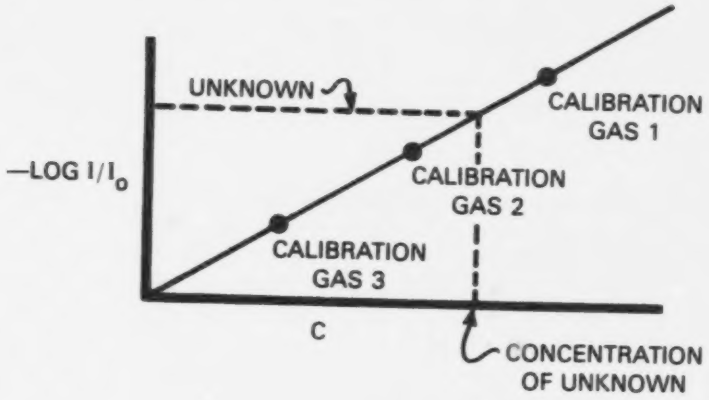


FIGURE 3-7

CALIBRATION CURVE FOR THE BEER-LAMBERT RELATION

Spectroscopic and nonspectroscopic techniques, such as polarography and electrocatalysis, will be examined in the subsequent chapter.

3.3 References

1. U.S. EPA, "Standards of Performance for New Stationary Sources," Code of Federal Regulations, 40 CFR, Part 60 Appendix B.
2. Ludwig, C. B., and Griggs, M., "Application of Remote Techniques in Stationary Source Air Emission Monitoring," EPA-340/1-76-005, June 1976.

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CHAPTER 4

CONTINUOUS MONITORS FOR OPACITY MEASUREMENTS

4.1 Opacity and Transmittance

The regulations require that an opacity monitor or transmissometer be installed on all new coal- and oil-fired steam generators with a capacity greater than 73 megawatts. The regulations covering opacity were made primarily to provide the plant operator with a means of checking the operation of the source control equipment. However, the opacity monitor is not, as yet, considered by EPA to be an enforcement tool for new sources, since the visible emissions observer (EPA Reference Method 9) is still used to enforce opacity standards. Data from opacity monitors may be used as evidence (see 40 CFR 60.11 and 42 FR 26205 5/23/77) in cases where there is a question of an opacity violation. Opacity monitors on existing sources may be used for compliance purposes, depending on the State regulations. In addition, the opacity monitor can serve as a process control instrument by optimizing combustion conditions or control device efficiency.

The term "transmissometer" comes from a combination of "transmission" and "meter." As mentioned in the previous chapter, when light passes through a plume or flue, some of the light will be scattered and absorbed by particulate matter in the plume. The absorbed and scattered light will not reach the detector on the other side of the flue gas and will be lost to observation. The transmission of the light through the gas is, therefore, decreased. A transmissometer is essentially a meter that gives a quantitative value of the decrease in light transmission.

If light is not able to penetrate through a plume, the plume is said to be opaque – the opacity of the plume is 100 percent. Transmittance and opacity can be related in the following manner:

$$\text{Percent Transmittance} = 100 - \text{Percent Opacity}$$

Therefore, if a plume or object is 100 percent opaque, the transmittance of light through it is zero. If it is not opaque (zero percent opacity), the transmittance of light will be 100 percent. A plume from a stationary source rarely will have either zero or 100 percent opacity, but some intermediate value. In the New Source Performance Standards (NSPS), the opacity limits have been established for a number of stationary sources. The following new sources are required to perform continuous monitoring for opacity, and to maintain the opacity within the standard shown:

	Percent Opacity Limit
Fossil-Fuel-Fired Steam Generators	20
Petroleum Refineries (Catalytic Cracker)	30
Ferroalloy Production Facilities (Submerged Electric Arc Furnaces)	15
Iron and Steel Plants (Electric Arc Furnaces)	3
Primary Copper, Lead, and Zinc Smelters	20
Kraft Pulp Mills (Recovery Furnace)	35

4.2 The Transmissometer

A transmissometer may be constructed using either a single-pass system (Figure 4-1) or a double-pass system (Figure 4-2). In the single-pass system, a lamp projects a beam of light

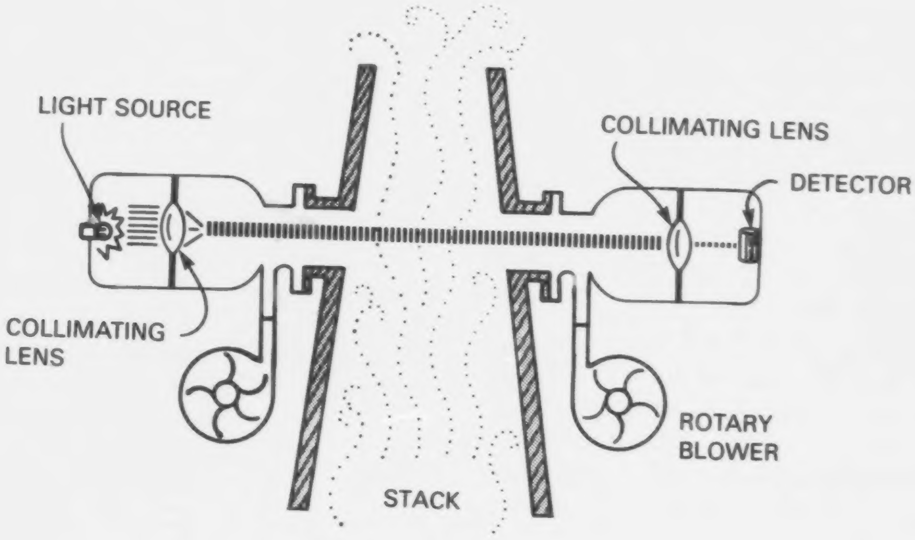

LIGHT SOURCE
COLLIMATING LENS
DETECTOR
COLLIMATING LENS
ROTARY BLOWER
STACK

FIGURE 4-1

SINGLE-PASS TRANSMISSOMETER SYSTEM

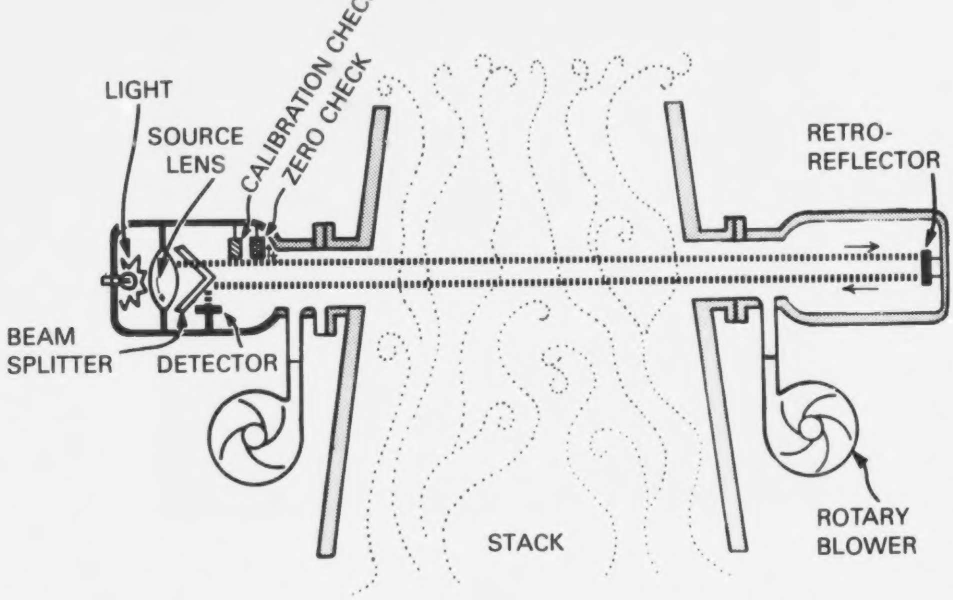


FIGURE 4-2

DOUBLE-PASS TRANSMISSOMETER SYSTEM

across the stack or duct leading to the stack, and the amount of light transmitted through the flue gas is sensed by a detector. Such instruments can be made rather inexpensively; however, they often do not satisfy specific EPA criteria for system zero and calibration checks. The double-pass system shown in Figure 4-2 houses both the light source and light detector in one unit. By reflecting the projected light from a mirror on the opposite side of the stack, systems can be easily designed to check all of the electronic circuitry, including the lamp and photodetector as part of the operating procedure. Most transmissometer systems include some type of air purging system or blower to keep the optical windows clean. In the case of stacks with a positive static pressure, the purging system must be efficient or the windows will become dirty, leading to spuriously high readings. Figures 4-3 and 4-4 show a typical installation of a double-pass transmissometer.

As mentioned in Chapter 1, EPA does not recommend specific manufacturer models. Since most stationary sources have unique monitoring problems, the Performance Specification Test is used as a procedure for assuring that the instrument will operate properly once mounted on a stack or duct. In addition, the transmissometer itself must satisfy several design specifications. In order for a specific opacity monitoring installation to be approved, it must meet these criteria.

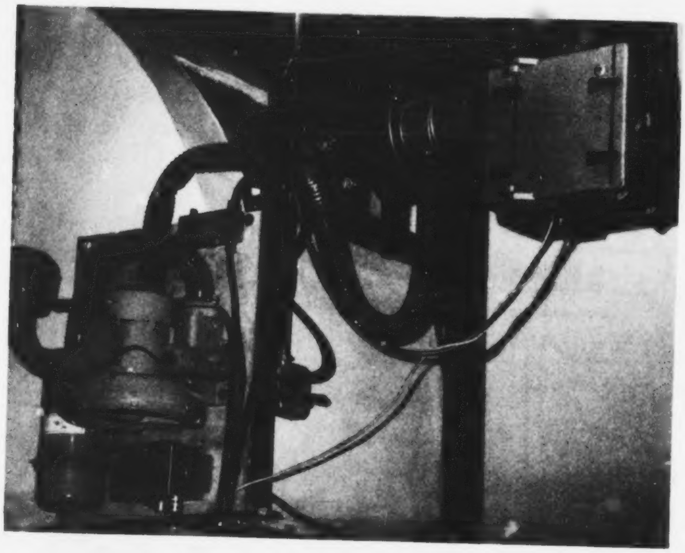


FIGURE 4-3

DOUBLE-PASS TRANSMISSOMETER INSTALLED AT EPA SOURCE SIMULATOR FACILITY, RESEARCH TRIANGLE PARK, NC

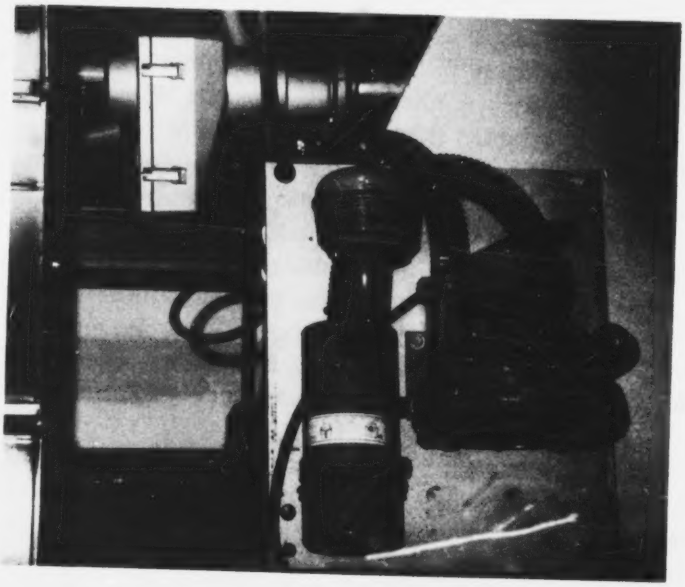


FIGURE 4-4

RETROREFLECTOR ASSEMBLY AT THE FACILITY

4.3 Design Specifications

There are essentially seven design criteria that must be met by an opacity monitor:

1. *Spectral Response* — The system must project a beam of light with the wavelength of maximum sensitivity lying between 500 and 600 nm. Also, no more than 10 percent of this peak response can be outside of the range of 400 to 700 nm.
2. *Angle of Projection* — The angle of the light cone emitted from the system is limited to 5 degrees.
3. *Angle of View* — The angle of the cone of observation of the photodetector assembly is limited to 5 degrees.
4. *Calibration Error* — Using neutral density calibration filters, the instrument is limited to an error of 3 percent opacity.
5. *Response Time* — The transmissometer system must detect and identify 95 percent of the value of a step change in opacity within 10 seconds.
6. *Sampling* — The monitoring system is required to complete a minimum of one measuring cycle every 10 seconds and one data recording cycle every 6 minutes.
7. *System Operation Check* — The monitor system is to include a means of checking the "active" elements of the system in the zero and calibration procedures.

Check the opacity monitoring instrument specifications before purchasing to assure that it satisfies these minimum requirements. Failure to do so may mean that the monitor will not be accepted by EPA.

There are several reasons for establishing these design specifications; the most important is that there is no widely available independent method of checking the opacity. Instead, it is assumed that if the system is designed correctly and if it can be checked with filters for accuracy, it should be able to give correct flue-gas opacity readings. The rationale behind each of the design specifications follows.

4.3.1 Spectral Response

The transmissometer is required to project a beam of light in the visible or photopic region — that portion of the electromagnetic spectrum to which the human eye is sensitive (Figure 4-5).

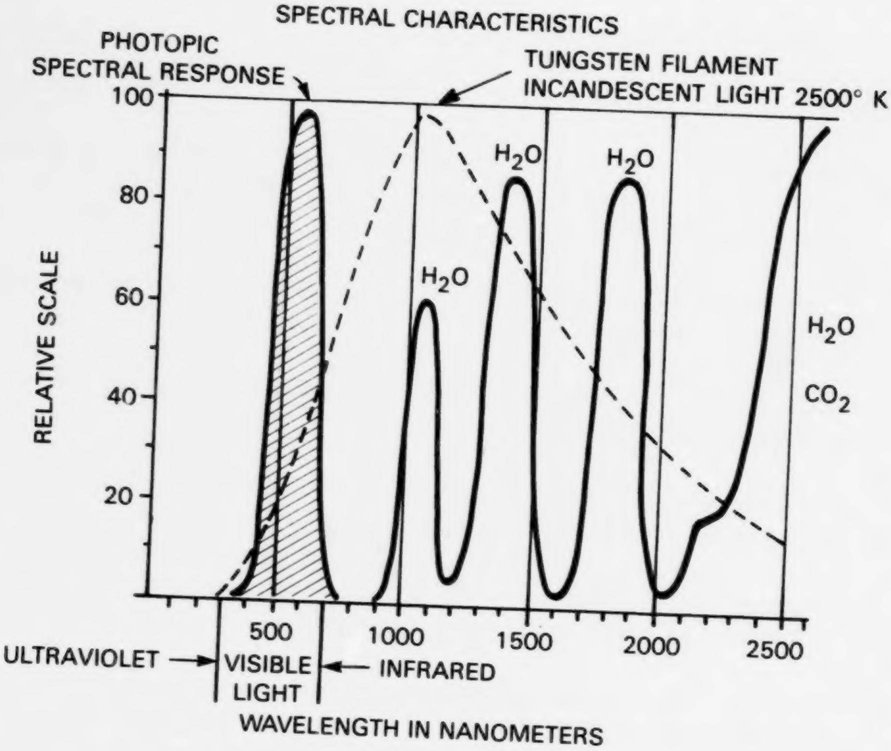


FIGURE 4-5

ELECTROMAGNETIC SPECTRUM
AND FACTORS THAT AFFECT OPACITY MEASUREMENTS

There are three reasons for specifying this region.

1. It was originally hoped to correlate the opacity readings of the transmissometer with those of the visible emissions observer performing EPA Method 9. If the transmissometer does project light in this region, generally the reading will be comparable. However, problems of background light contrast, acid aerosol formation, etc., may cause the readings of visible emissions observer to differ from those of the transmissometer.

2. Water and carbon dioxide absorb light at wavelengths higher than 700 nm. If the transmissometer projected light in this region (as some earlier systems did in fact), any water vapor or carbon dioxide in the flue gas would take away some of the light energy by absorption processes; a high opacity reading would result (see absorption regions in Figure 4-5). For example, since this would unduly penalize the operator of a fossil-fuel-fired boiler, filters or special optics are required to limit the spectral response of the transmissometer.

3. Particles less than 0.5 microns in size will scatter light more effectively if the light has a wavelength in the region of 550 nm rather than at higher wavelengths (Figure 4-6).

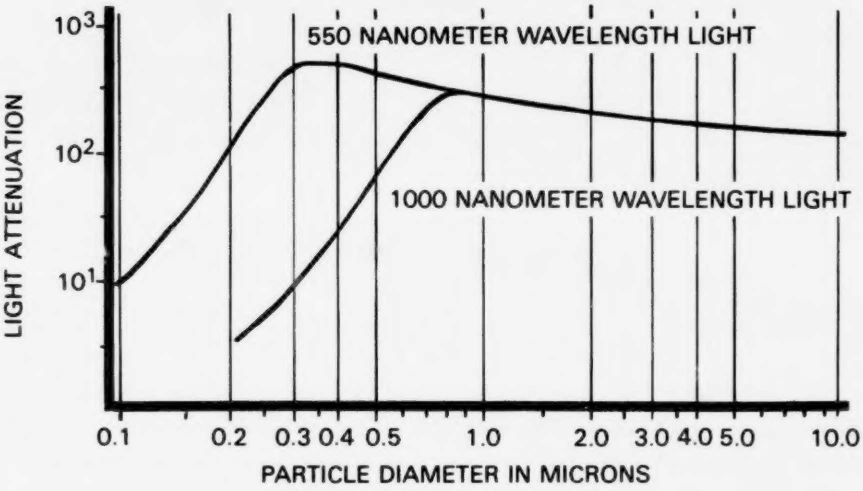


FIGURE 4-6

PARTICULATE ATTENUATION OF INCIDENT LIGHT

Industrial sources utilizing particulate control devices emit particulates in the lower size ranges. Consequently, shorter light wavelengths are needed to provide meaningful opacity measurements.

4.3.2 Angle of Projection

The ideal transmissometer would have a collimated laser-sharp beam projected across the stack. When a beam diverges, particles outside of the transmissometer path absorb or scatter the light. Thus, light energy would be lost outside of the path, which would appear as higher opacity readings. Since constructing sharply collimated instruments is expensive, specifications have been given to limit beam divergence to 5 degrees, as shown in Figure 4-7.

The procedure for checking the angle of projection is to draw an arc with a 3-meter radius, then measure the light intensity at 5-cm intervals for 26 cm on both sides of the center line, both horizontally and vertically.

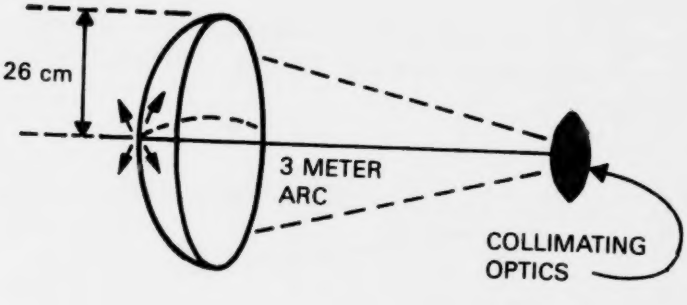

26 cm
3 METER
ARC
COLLIMATING
OPTICS

FIGURE 4-7

ANGLE OF PROJECTION

4.3.3 Angle of View

The reason for specifying the angle of view of the detector assembly is similar to that for the projection angle specification. In this case, if the angle of view were too great, the detector could possibly pick up light outside of the transmissometer light path. It would, therefore, "see" more light energy than it should, and the transmissometer readings would be lower than true (Figure 4-8).

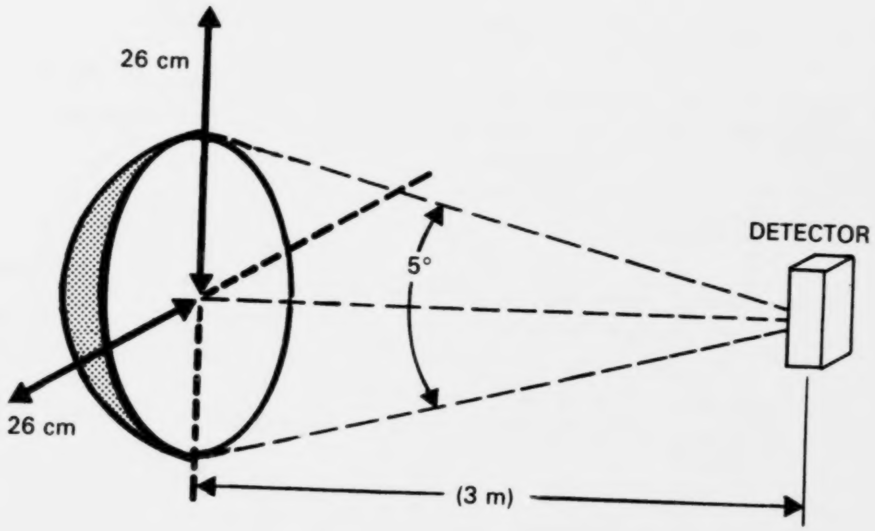

26 cm
DETECTOR
5°
26 cm
(3 m)

FIGURE 4-8

ANGLE OF VIEW

The angle of view may be checked by using a small nondirectional light source to find out where, on an arc of 3-meter radius, a signal will appear. Generally, however, the projection and detection angles are determined by the instrument manufacturer.

4.3.4 Calibration Error

Transmissometers are calibrated with neutral density filters corresponding to a given percent opacity. The calibration error test is the best method for checking the accuracy of the instrument. For that reason, before an instrument is placed on a duct or stack, the instrument response to calibration filters should be within 3 percent of the predetermined filter values.

4.3.5 System Response Time Test

The regulations require a transmissometer system to measure opacity every 10 seconds. An approvable transmissometer must reach 95 percent of a calibration filter value within 10 seconds after being slipped into the light path in order to satisfy this design specification.

4.3.6 Sampling Criteria

EPA regulations specify that an approvable transmissometer must be able to complete a minimum of one measuring cycle every 10 seconds (40 CFR 60.13e). Also, some provision must be made in the monitoring system to record an averaged reading over a minimum of 24 data points every 6 minutes.

These specifications were made so that the opacity monitor would provide information corresponding to the behavior of the particulate control equipment and to the data obtained by the visible emissions observer. (EPA Method 9 requires the reading of 24 plumes at 15-second intervals. See also, the discussion on page 4-17.)

4.3.7 System Operation Check

The system operation check often has not been recognized by instrument vendors as one of the design criteria for transmissometer systems. In 40 CFR 60.13e3, it is stated that:

> . . .procedures shall provide a system check of the analyzer internal optical surfaces and all electronic circuitry including the lamp and photodetector assembly.

This means that when calibrating or zeroing the instrument, the lamp, photodetector, etc., used should be the same as that used in measuring the flue gas opacity. Most single-pass opacity monitors would not be acceptable under EPA design specifications, since a zero reading could not be obtained unless the stack was shut down. Figure 4-9 shows the automatic zeroing mirror on a double-pass transmissometer.

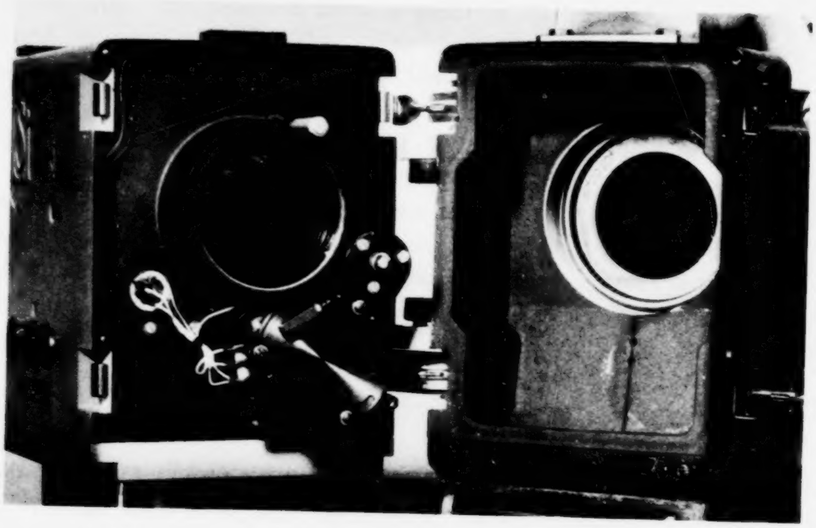


FIGURE 4-9

LEAR SIEGLER RM41-P SHOWING INSTRUMENT "ZERO" REFLECTOR

4.4 Installation Specifications

After an approved transmissometer has been selected by the source operator, the instrument must be installed and checked for proper operation on the source itself. There are several points that must be considered when installing a transmissometer:

- It must be located across a section of duct or stack that will provide a representative measurement of the actual flue gas opacity.
- It must be downstream from the particulate control equipment and as far away as possible from bends and obstructions.
- It must be installed in the plane of the bend if located in a duct or stack following a bend.
- It should be installed in an accessible location.
- It may be required to demonstrate that it is obtaining representative opacity values at its installed location.

These installation specifications are designed so that the transmissometer will measure the actual flue gas opacity or "an optical volume which is representative of the particulate matter flowing through the duct or stack." Figure 4-10 shows some of the problems in particulate matter flow distribution occurring in an exhaust system.

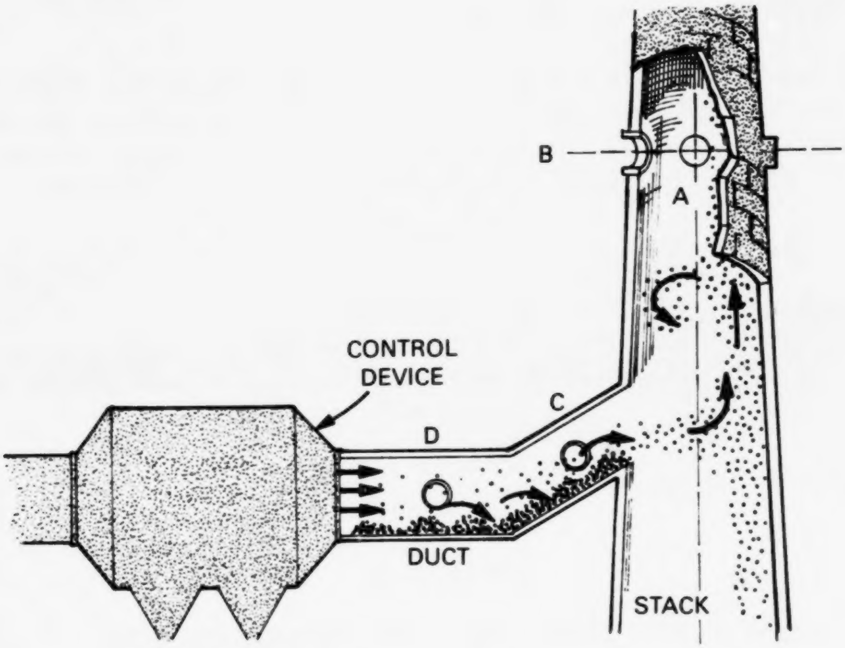


FIGURE 4-10

TRANSMISSOMETER SITING

Particulate matter may settle in ducts or stratify in the flue gas stream depending upon the construction of the exhaust system. In Figure 4-10 the plane of the bend is formed by the stack and the duct (in this case, the plane of the paper).

If a transmissometer were located perpendicular to this plane, such as at point A, Figure 4-10, a large portion of the particulate matter would not be seen. A transmissometer located at B would be in the plane of the bend and would be sensing a cross-section of the total particulate flow. Location C would not be appropriate for an opacity monitor, since the monitor would not be in the plane formed by the horizontal duct and the breeching duct. A monitor at location C also would not satisfy criterion 1 or 2, since settling of particulate matter might not provide a representative sample, and the location is close to two bends in the exhaust system. Location D would be one of the most ideal points for monitoring, since the transmissometer would be more *accessible* and might be more carefully maintained than if it was in location B. Location D comes after the control device and does not follow a bend. The only problem that might arise is the settling of particulate matter in the duct and possible re-entrainment to give unrepresentative opacity readings. An examination of the opacity profile over the depth of the duct might be necessary to place the monitor at this point.

A portable in-situ, double-pass monitor, such as that shown in Figure 4-11, may be found useful in examining possible installation sites. Proper monitor siting is very important to the source operator, since an inappropriate choice for the location of a monitor may cause measurement problems and may be costly, particularly if resiting were necessary.

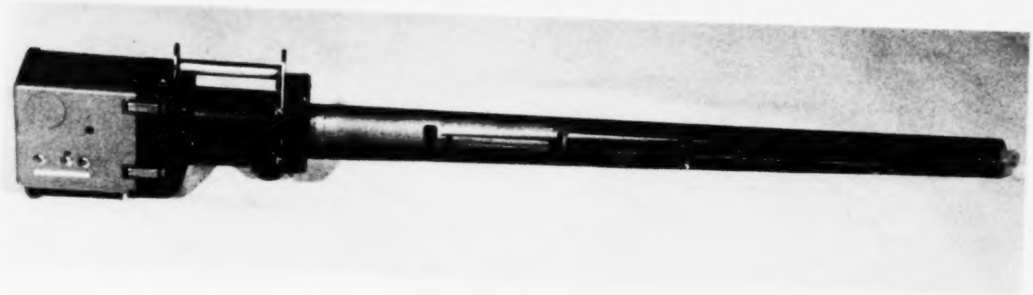


FIGURE 4-11

LEAR SIEGLER RM41-P PORTABLE TRANSMISSOMETER

4.5 The Performance Specification Test

Before an opacity monitoring system can be used for EPA reporting requirements, it must undergo the Performance Specification Test. Since most sources differ in operational design and construction, a given monitor might perform well at one source, but might produce unacceptable data at another. Also, since differences in particulate stratification, vibration, temperature, etc., affect operation, the opacity monitor must pass the performance test at the location for which it was intended; design specifications alone are not sufficient for approval (in contrast to ambient air monitors). A brief description of the test is given here; specific test details are given in Chapter 11.

For the Performance Specification Test, the opacity monitors must undergo a 1-week conditioning period and a 1-week operational test period. In the conditioning period, the monitor is merely turned on and is run in a normal manner. This is essentially a burn-in period for the new instrument to eliminate those problems that one might expect for a new device. In the operational test period, the monitor is run for 1 week without any corrective maintenance, repair, or replacement of parts other than that required as normal operating procedure. During this period, 24-hour zero and calibration drift characteristics are determined. If the instrument is poorly designed or if it is poorly mounted, these problems should become evident from the drift data, and corrective action would have to be taken. Only zero, calibration drift, and response time data are necessary for the performance test. The acceptable limits for these parameters are given in Table 4-1.

TABLE 4-1

OPACITY MONITOR PERFORMANCE SPECIFICATIONS

Conditioning Period	– 1 week
Operational Period	– 1 week
Zero Drift (24 Hr)	– ≤2% opacity
Calibration Drift (24 Hr)	– ≤2% opacity
Response Time	– 10 seconds

4.6 Data Reporting Requirements

After an opacity monitoring system has passed the Performance Specification Test, it may be used to monitor the source emissions. New sources required to monitor opacity are required to report excess emissions on a quarterly basis. Since opacity standards are based on the opacity of the plume at the stack exit, the in-stack transmissometer data must be corrected to the pathlength at the stack exit.

A term used in opacity monitoring called optical density (O.D.) is related to opacity in the following manner:

$$\text{O.D.} = \log_{10} \frac{1}{1 - \text{opacity}}$$

This is a useful expression since, by considering the properties of particulate scattering and absorption, a linear relationship between particulate concentration and optical density results. The Beer-Lambert law for the transmittance of light through an aerosol states that

$$T = e^{-naQL}$$

or

$$(1 - O) = e^{-naQL}$$

where:

T = transmittance

n = number concentration of particles

a = projected area of the particles

Q = particle extinction coefficient

L = light path through the aerosol

O = opacity

If the logarithm is taken of both sides, then

$$\log(1 - O) = 0.434\ naQL$$

where:

0.434 is the conversion factor between the natural and base 10 logarithm

and

$$\log \frac{1}{(1 - O)} = KcL$$

where:

K = a constant describing the characteristics of the particle scattering

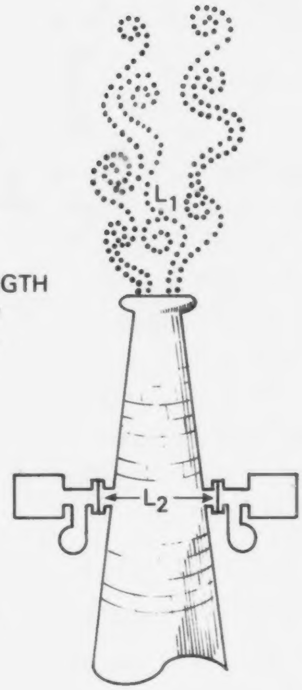
L = the pathlength

c = the concentration (being proportional to n)

This merely states that O.D. = Kc, or that the optical density is proportional to the particulate concentration.

If the diameter of the stack exit differs from the transmissometer pathlength, a relationship between the two can be derived from a consideration of the optical density. Refer to Figure 4-12.

L_1 = EMISSION OUTLET PATHLENGTH
L_2 = MONITOR PATHLENGTH
O_1 = EMISSION OPACITY
O_2 = MONITOR OPACITY



$$O_1 = 1 - (1 - O_2)^{L_1/L_2}$$

FIGURE 4-12

RELATION BETWEEN EMISSION OPACITY AT PLUME EXIT AND MONITOR OPACITY IN DUCT

Assuming that the concentration of the particulate matter is the same at L_1 as it is at L_2,* the optical density across each path will be

$$O.D._1 = \log \frac{1}{(1 - O_1)} = KcL_1$$

$$O.D._2 = \log \frac{1}{(1 - O_2)} = KcL_2$$

Dividing the two

$$O.D._1 = \frac{L_1}{L_2} O.D._2$$

---

*Note that the velocities will change in order that the volumetric flowrate can remain the same.

Taking the antilogarithms and solving for opacity, it is found that

$$O_1 = 1 - (1 - O_2)^{L_1/L_2}$$

Optical density is a useful parameter for calculating stack exit correlations for other cases. For instance, if two ducts fed into a single stack and two transmissometers were used to monitor the opacity (Figure 4-13), the following expression can be derived:

$$O.D._3 = \frac{O.D._1 A_1 v_1 \frac{L_3}{L_1} + O.D._2 A_2 v_2 \frac{L_3}{L_2}}{v_1 A_1 + v_2 A_2}$$

where A_1 and A_2 are the cross-sectional areas of each duct at the point of measurement, and v_1 and v_2 are the flue gas velocities in each duct. If the areas and velocities of each duct are identical, this simplifies to

$$O.D._3 = \frac{O.D._1 \frac{L_3}{L_1} + O.D._2 \frac{L_3}{L_2}}{2}$$

The opacity at the stack exit can then be obtained from the optical density, $O.D._3$.

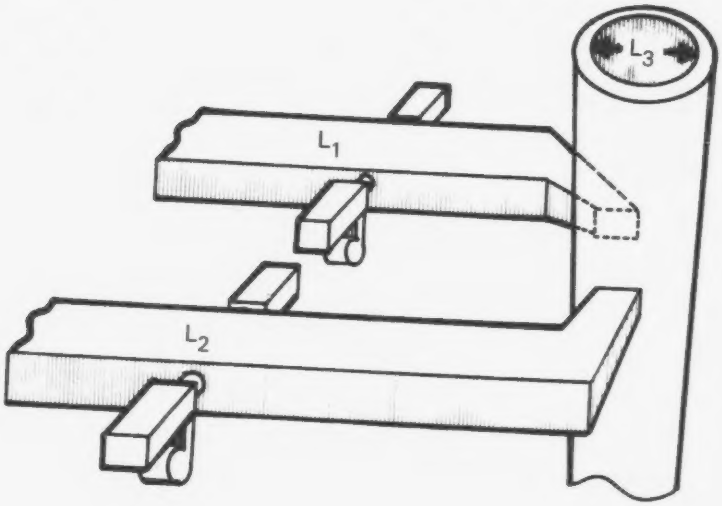


FIGURE 4-13

TWO DUCTS ENTERING COMMON EXIT STACK

To satisfy the NSPS continuous monitoring regulations, the opacity must be measured every 10 seconds. The data must be averaged and recorded every 6 minutes, with a minimum of 24 equally spaced data points being used in the average. Dividing 24 into 6 minutes gives a measuring time of 15 seconds. This does not correspond to the minimum required measuring time of 10 seconds. The discrepancy arises because a visible emissions observer performing EPA Method 9 is required to average 24 plume opacity observations at 15-second intervals, and the continuous opacity monitor reporting requirements were made to correspond to EPA Method 9.

The transmissometer system must be able to record the average of at least 24 equally spaced opacity readings taken over a 6-minute period. Any readings in excess of the applicable standard (e.g., 20 percent opacity for a coal-fired boiler) must be reported. Also, a report of equipment malfunctions or modifications must be made. Although the recorded data do not have to be reported to EPA unless excessive emissions occurred, the data must be retained for a minimum of 2 years.

4.7 Opacity Monitor Selection

The plant operator who selects an opacity monitor for a given application must consider many factors. If the monitor must satisfy the NSPS continuous monitoring regulations, one of the first things to check would be whether the instrument satisfies the design specifications established by the EPA. Additional criteria would be the capability of satisfying the Performance Specification Test and the frequency-of-repair record.

Cost is always a major factor. Reliable transmissometers that require more frequent routine maintenance than a top-of-the-line instrument are available at relatively lower cost. One of the major factors in this consideration is the availability of an instrument technician at the plant who could periodically check the monitor.

The vendors of opacity monitors are divided into those who market single-pass instruments and those who market the double-pass systems. Most of the double-pass systems will satisfy the EPA design criteria, and there are now a number of these monitors that have passed the Performance Specification Test after having been placed on sources. The single-pass instruments are less expensive than the double-pass systems, but most are incapable, by virtue of their design, of meeting the EPA system zero and calibration checks unless the stack is cleared every 24 hours. Single-pass systems, however, may be applied in situations where there are less stringent requirements, such as process monitoring or bag breakage in fabric filter particulate control systems. Refer to Chapter 9 for a detailed outline of selection procedures for opacity monitors and a list of vendors.

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Sem, G. J., and Borgos, J. A., "State of the Art: 1971 Instrumentation for Measurement of Particulate Emissions from Combustion Sources," Vol. IV, NTIS PB-231-919/AS, Nat. Tech. Inform. Serv., Springfield, Virginia, 1973.

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CHAPTER 5

CONTINUOUS MONITORS FOR THE MEASUREMENT OF GASES

5.1 Introduction

Sources required to install continuous-gaseous emission monitors are faced with the problem of selecting instruments that will give data that are representative of the actual source emissions. The problems that are encountered in a sulfuric acid plant will be different from those found at a primary smelter. Even within a given source category, the plant design often will dictate the choice of a monitoring system. For example, an in-situ sulfur dioxide monitor may work well on a coal-fired power plant that uses an electrostatic precipitator to control particulate emissions, but it may encounter problems when placed on a facility operating at high temperatures.

The proper selection or evaluation of a gas analyzer requires a knowledge of the practical differences between extractive and in-situ systems and a knowledge of the operating principles of the analyzers themselves. The remainder of this chapter and the next four chapters present a basis for such an evaluation. These chapters cover:

- Extractive Monitoring Instruments
- Extractive System Design
- In-Situ Monitoring Systems
- Recording Systems
- Selection Procedures

The extraction of a sample gas from a stack or duct presents a number of problems for the first class of continuous analyzers. To obtain accurate results, a sample representative of the exhaust gas constituents first must be selected before entering the monitor itself. The sample must be processed by removing particulate matter, condensing water vapor, and, in some cases, removing specific gases that interfere in the analytical method. In-situ monitors, on the other hand, do not require the removal of particulates or water vapor. The analytical methods used in this class of monitor have been chosen to avoid these interferences. In-situ monitors do, however, have limitations in their application. If a stack or duct contains entrained water in the form of liquid droplets, light scattering problems and absorption of the pollutant gases in the liquid may cause the instrument values to differ from those obtained by the EPA reference method. The choice of the type of system (either extractive or in-situ) to be used in a given application often will depend upon features of the plant design. The choice of a specific instrument will depend upon variables ranging from practical considerations, such as cost, to purely analytical factors, such as the scientific principle that will give the most accurate concentration data for a given pollutant.

The selection of a monitor also is dependent upon the EPA criteria for the Performance Specification Test. A gaseous-emissions monitoring instrument must meet the following specifications after it is installed on the source:

	SO_2 and NO_x	O_2 or CO_2
Accuracy	20%	–
Calibration error	5%	–
Zero drift (2 hr & 24 hr)	2% of span	<0.4% & <0.5% O_2 or CO_2
Calibration drift (2 hr & 24 hr)	2.5% of span	<0.4% & <0.5% O_2 or CO_2
Response time	15 min (max)	10 min (max)
Operational period	168 hrs	168 hrs

The Performance Specification Tests 2 and 3 for gases will be discussed in Chapter 11.

Gaseous emission monitors, both extractive and in-situ, can be characterized by the principles of chemical physics used. The methods used in source level analyzers can be grouped into three major categories:

Absorption Spectrometers

Luminescence Analyzers

Electroanalytical Methods

Extractive monitors utilize methods from all of these categories, whereas in-situ systems generally use spectroscopic absorption methods. An exception to this is an in-situ electrocatalytic cell that monitors oxygen. There are a few special methods that do not fit into this classification: paramagnetism is used in oxygen analyzers and thermal conductivity is used in a few SO_2 monitors. These methods will be discussed separately.

5.2 Extractive Analyzers

As mentioned in Chapter 2, extractive analyzers have had a longer developmental period than the in-situ monitors. In the past, either existing ambient air monitors or common laboratory instruments were modified for source-level monitoring applications. Problems tended to arise with the inevitable dilution systems and delicate nature of some of these systems. Many of these earlier problems now have been solved. Extractive analyzers are now designed specifically to monitor at-source-level concentrations and are constructed to withstand the rigors of a plant environment.

5.2.1 Extractive Analyzers – Spectroscopic Methods of Analysis

5.2.1.1 Nondispersive Infrared Analyzers

Nondispersive Infrared (NDIR) analyzers have been developed to monitor SO_2, NO_x, CO, CO_2, and other gases that absorb in the infrared, including hydrocarbons. An NDIR analyzer is basically an instrument that does not disperse the light that is emitted from an infrared source. Not dispersing the light means not breaking up the emitted radiation into its component wavelengths with a prism or diffraction grating. Dispersive instruments, or dispersive absorption spectrometers, are most often found in the chemistry or physics laboratory where they are commonly used to identify molecular compounds from their infrared absorption spectra by continuously scanning over many wavelengths. NDIR instruments utilize a broad band of light that is centered at an absorption peak of the pollutant molecule, such as that shown in Figure 5-1.

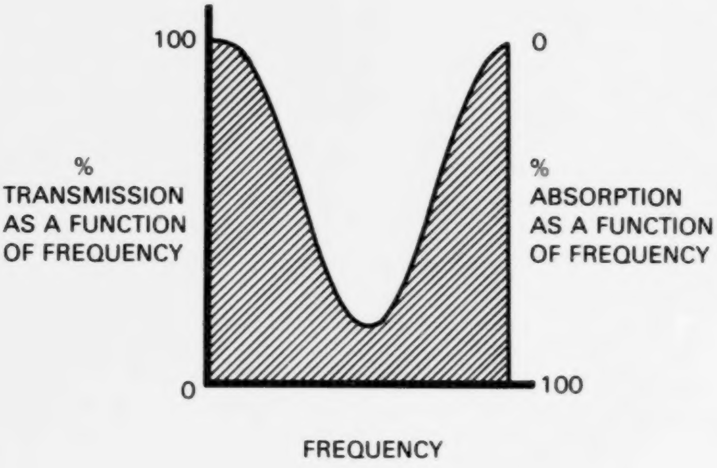


FIGURE 5-1

A LORENTZIAN ABSORPTION CURVE

This broad band is usually selected from all the light frequencies emitted by the infrared source, by using a bandpass filter. Table 5-1 gives the band centers for several of the gases found in source emissions.

In a typical NDIR analyzer, such as that shown in Figure 5-2, infrared light from a lamp or glower passes through two gas cells — a reference cell and a sample cell. The reference cell generally contains dry nitrogen gas, which does not absorb light at the wavelength used in the instrument. As the light passes through the sample cell, pollutant molecules

TABLE 5-1

INFRARED BAND CENTERS OF SOME COMMON GASES*

Gas	Location of Band Centers (μm)	Wave Number (cm^{-1})
NO	5.0-5.5	1800-2000
NO_2	5.5-20	500-1800
SO_2	8-14	700-1250
H_2O	3.1	1000-1400
	5.0-5.5	1800-2000
	7.1-10	3200
CO	2.3	2200
	4.6	4300
CO_2	2.7	850-1250
	5.2	1900
	8-12	3700
NH_3	10.5	950
CH_4	3.3	1300
	7.7	3000
Aldehydes	3.4-3.9	2550-2950

*Table from LBL-1, "Instrumentation for Environmental Monitoring"

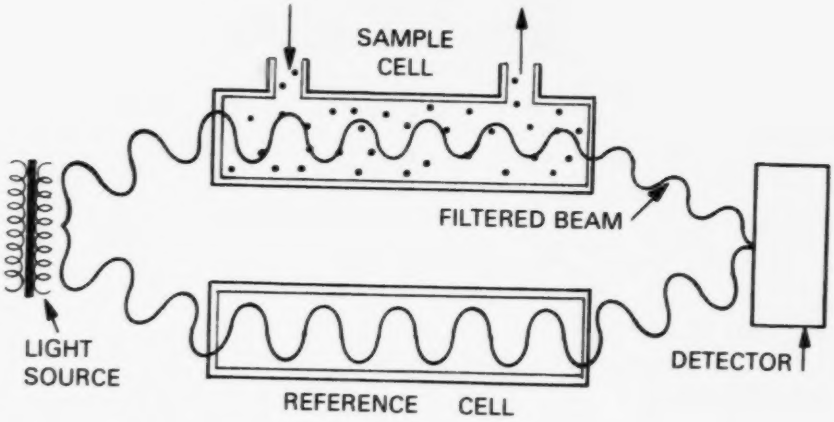

SAMPLE CELL
FILTERED BEAM
LIGHT SOURCE
REFERENCE CELL
DETECTOR

FIGURE 5-2

SIMPLIFIED SCHEMATIC DIAGRAM OF A NONDISPERSIVE INFRARED ANALYZER will absorb some of the infrared light. As a result, when the light emerges from the end of the sample cell, it will have less energy than when it entered. It also will have less energy than the light emerging from the reference cell. The energy difference is then sensed by some type of detector, such as a thermistor, a thermocouple, or microphone arrangement. Figure 5-3 shows one of the more common commercial arrangements for this type of system.

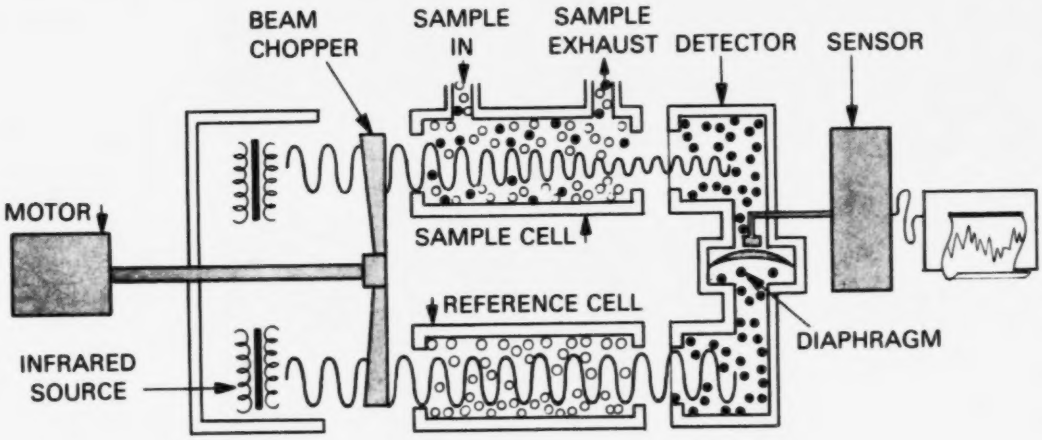


FIGURE 5-3

OPERATION OF THE "MICROPHONE" DETECTOR OF AN NDIR ANALYZER

Infrared radiation passes through a reference and a sample cell. The microphone type detector that is used consists of two chambers separated by a thin metal diaphragm, each chamber being filled with gas of the species being measured. When the infrared radiation strikes a pollutant molecule, the molecule will absorb light energy and will move faster. This greater agitation for a number of molecules produces heat. This heating, in turn, will increase the pressure in each chamber of the detector cell; however, the light that passed through the sample cell will have lost some of its energy to the pollutant molecules in the sample gas, and the sample chamber will not be heated as much as the reference chamber. As a result, a pressure difference will develop, and the diaphragm will be distended.

The greater the amount of the pollutant gas in the sample, the greater the displacement. The displacement is detected as a capacitance change by the instrument electronics and is ultimately processed to give a reading for the concentration of pollutant in the sample. The rotating wheel chopper is used to create an alternating signal in the detector and, hence, will make the signal easier to detect and amplify. Figure 5-4 shows a typical configuration of a double-beam NDIR analyzer.

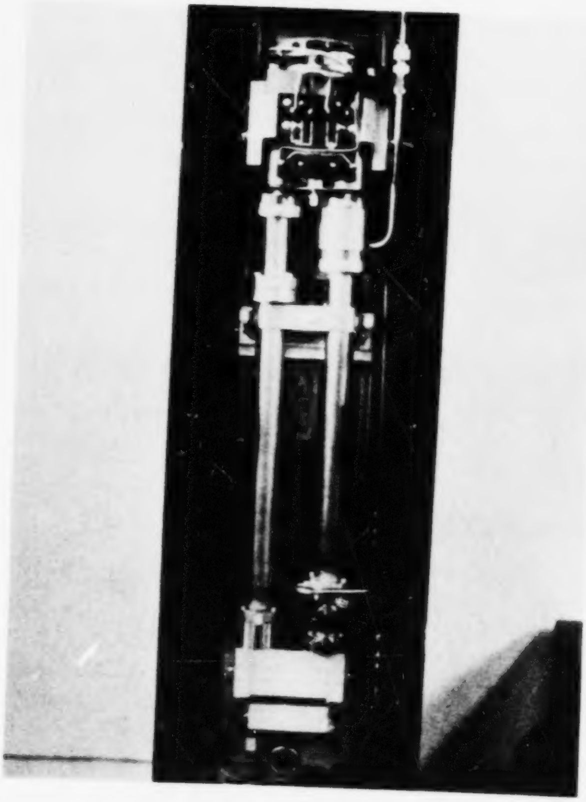


FIGURE 5-4

INTERNAL VIEW OF A BECKMAN NDIR ANALYZER

A common problem with analyzers that use a detecting arrangement, as shown in Figure 5-3, is that gases that absorb light in the same spectral region as the pollutant molecule will cause a positive interference in the measurement. For example, water vapor and CO_2 will interfere in the measurement of CO using this arrangement (see also Table 5-1). These gases must be removed by some scrubbing system before the sample gas enters the analyzer. A unique solution to this problem is to put the detector cells in series instead of in parallel, as shown in Figure 5-5.

The front chamber of the detector will absorb the infrared radiation primarily at the frequencies in the center of an absorption band, such as that shown in Figure 5-1. Since the front cell takes away energy from the light beam at the center frequencies, the rear measuring chamber will absorb more of the energy in the outer edges of the band than it will from the center. The geometries and gas concentrations of each measuring chamber are chosen so that the pressure in each will be the same as when no pollutant molecules are in the sample cell. Once pollutant molecules are introduced into the sample cell, the amount of energy reaching the detector will be reduced; however, most of this reduction

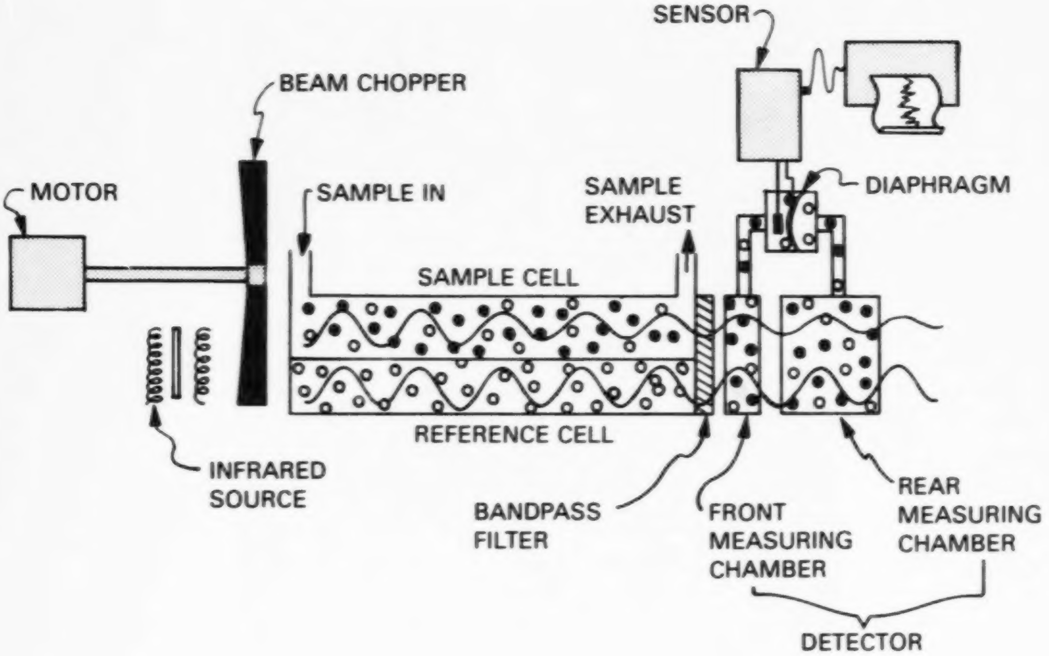

SENSOR
BEAM CHOPPER
MOTOR
SAMPLE IN
SAMPLE EXHAUST
DIAPHRAGM
SAMPLE CELL
REFERENCE CELL
INFRARED SOURCE
BANDPASS FILTER
FRONT MEASURING CHAMBER
REAR MEASURING CHAMBER
DETECTOR

FIGURE 5-5

OPERATION OF A "NEGATIVE FILTER" NDIR ANALYZER

will arise from absorption at the band center, and the front chamber of the detector will be less affected by the incoming radiation. The front chamber therefore, will be cooler than the rear chamber, causing a pressure difference and a distention of the thin-metal diaphragm. This method is often called negative filtering.

Interfering species generally will not have an absorption band that coincides exactly with that of the species of interest. In such a case, absorption will occur relatively evenly over the region, and the interference will be minimized. Several monitors have been constructed utilizing this principle and need less supportive apparatus to remove such species as water and CO_2. A photograph of the Bendix 8501 single-beam analyzer, which utilizes this method, is shown in Figure 5-6.

The advantages of the NDIR-type analyzers are their relatively low cost and the ability to apply the method to many types of gases. Generally, a separate instrument is required for each gas, although several instruments have interchangeable cells and filters to provide more versatility. Problems associated with the method are those that arise from interfering species, the degradation of the optical system caused by corrosive atmospheres, and in some cases, limited sensitivity. The microphone type detectors are sensitive to vibration and often require both electronic and mechanical damping, for example, by placing the instrument on a foam insulation pad.

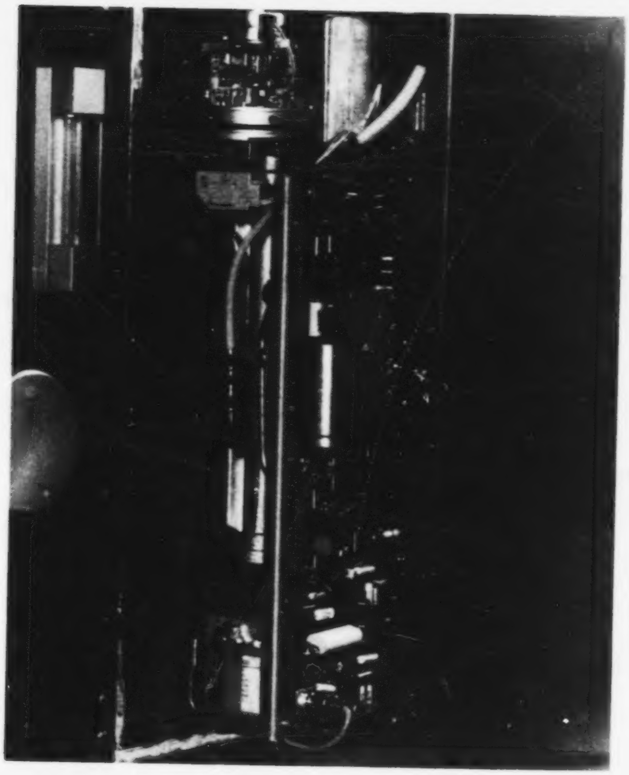


FIGURE 5-6

INTERNAL VIEW OF A BENDIX NDIR ANALYZER

5.2.1.2 Nondispersive Ultraviolet Analyzers (NDUV) – Differential Absorption

Several available nondispersive systems use light in the ultraviolet and visible regions of the spectrum rather than in the infrared. To analyze for SO_2, these instruments utilize one of the narrow absorption bands of the ultraviolet absorption spectrum (Figure 5-7).

NO_2 may be determined by taking advantage of its absorption spectrum in the visible region. The instruments that are designed to work within these regions do so in a manner somewhat different from the NDIR method discussed previously. Essentially, the analyzers measure the degree of absorption at a wavelength in the absorption band of the molecule of interest (280 nm for SO_2 and 436 nm for NO_2, for example). This is similar to the NDIR method, but the major difference is that a reference cell is not used. Instead, a reference wavelength, in a region where SO_2 or NO_2 has minimal absorption, is utilized. The rationale behind this method comes from the Beer-Lambert law (which was introduced in section 3.2.4):

$$I = I_o e^{-\alpha c l}$$

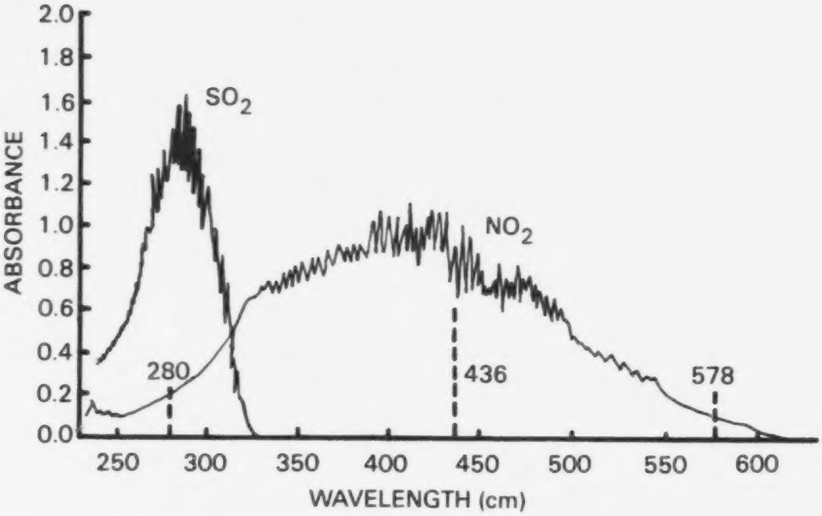


FIGURE 5-7

THE ULTRAVIOLET-VISIBLE SPECTRUM OF SO_2 AND NO_2

In the NDIR method, using a reference cell where $c_{reference} = 0$, two light intensities are compared:

$$I_{sample} = I_o e^{-\alpha c_{sample} l} \qquad I_{reference} = I_o e^{-\alpha c_{reference} l}$$

therefore

$$I_{reference} = I_o = \text{constant}$$

I_o remains constant, and I_{sample} can be related to it to obtain a concentration measurement. In the ultraviolet system, on the other hand,

$$c_{reference} = c_{sample} \neq 0$$

The absorption coefficients are wavelength dependent, and the reference wavelength is chosen so that $\alpha_{reference} = 0$.

$$I_{sample} = I_o e^{-\alpha c_{sample} l} \qquad I_{reference} = I_o e^{-\alpha_{reference} c_{sample} l}$$

$$\alpha_{reference} = 0$$

therefore;

$$I_{reference} = I_o = \text{constant}$$

The ratio between I_{sample} and I_o can then be taken to obtain a relation for the concentration.

$$\frac{I_{sample}}{I_{reference}} = \frac{I_o e^{-\alpha c_{sample} l}}{I_o}$$

and

$$c_{sample} = \frac{\log \frac{I_{sample}}{I_{reference}}}{\alpha l}$$

where,

l = known

α = known or instrument calibrated to account for the value

$I_{sample}/I_{reference}$ = detected by the instrument

This method of analysis is often termed differential absorption, since measurements are performed at two different frequencies. This method is not limited to extractive monitoring systems, but it also is used in both in-situ analyzers and remote sensors.

Figure 5-8 shows a schematic of one of the more typical NDUV monitors. Instead of using a reference cell (as in the NDIR systems), the instrument uses a reference wavelength at 578 nm. Light from the mercury discharge lamp passes through the sample cell to a beam splitter. The beam splitter, actually a semitransparent mirror, directs the light to two separate photomultiplier tubes. Narrow bandpass filters allow light of only the specified wavelengths to reach each of the photomultipliers. The reflected beam passes through a 578-nm filter and is used to generate the reference signal in the detector. The transmitted beam, however, passes through a 280-nm filter for an NO_2 monitor. Since SO_2 will absorb light at 280 nm (NO_2 at 436 nm), the amount of light or energy reaching the phototube will be less than that reaching the reference phototube. The resultant photomultiplier signals are amplified and processed to give a reading for the pollutant concentration. Nitric oxide (NO) does not absorb in the spectral region covered by the instrument and first must be quantitatively converted to NO_2 for subsequent analysis. This is done sequentially by stopping the flow in the NO_2 sample cell, pressurizing it with O_2, and waiting approximately 5 minutes for the NO to be converted to NO_2 by the excess oxygen. The NO is then determined from the difference in the readings before and after the reaction with oxygen.

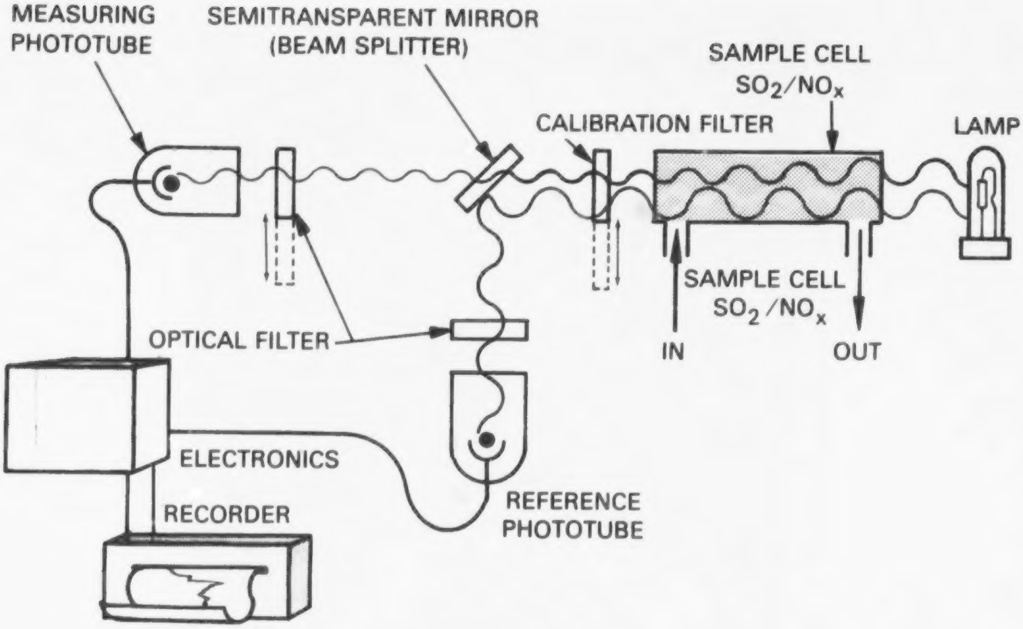

MEASURING PHOTOTUBE
SEMITRANSPARENT MIRROR (BEAM SPLITTER)
SAMPLE CELL SO_2/NO_x
CALIBRATION FILTER
LAMP
SAMPLE CELL SO_2/NO_x
IN
OUT
OPTICAL FILTER
ELECTRONICS
RECORDER
REFERENCE PHOTOTUBE

FIGURE 5-8

OPERATION OF A DIFFERENTIAL ABSORPTION NDUV ANALYZER

The extractive analyzers using differential absorption have proven to be reliable in monitoring source emissions. Several of the instrument models currently available are well built, since they were designed for in-plant environment (Figures 5-9 and 5-10).

The differential absorption SO_2 analyzers are somewhat more sensitive than are the NDIR counterparts. The sequential nature of the NO_x analysis may limit the utility of the method in some cases. As with all extractive monitoring systems, particulate matter should be removed before entering the analyzer. It is not necessary, however, to remove water vapor in some of these systems (DuPont, specifically). A heated sample line and heated cell prevent condensation in the analyzer. Since water does not absorb light in this region of the ultraviolet spectrum, no interference occurs.

5.2.2 Extractive Analyzers – Luminescence Methods of Analysis

5.2.2.1 General

Luminescence is the emission of light from a molecule that has been excited in some manner. Photoluminescence is the release of light after a molecule has been excited by ultraviolet, visible, or infrared radiation. The emission of light from an excited molecule created in a chemical reaction is known as chemiluminescence. The atoms of a molecule

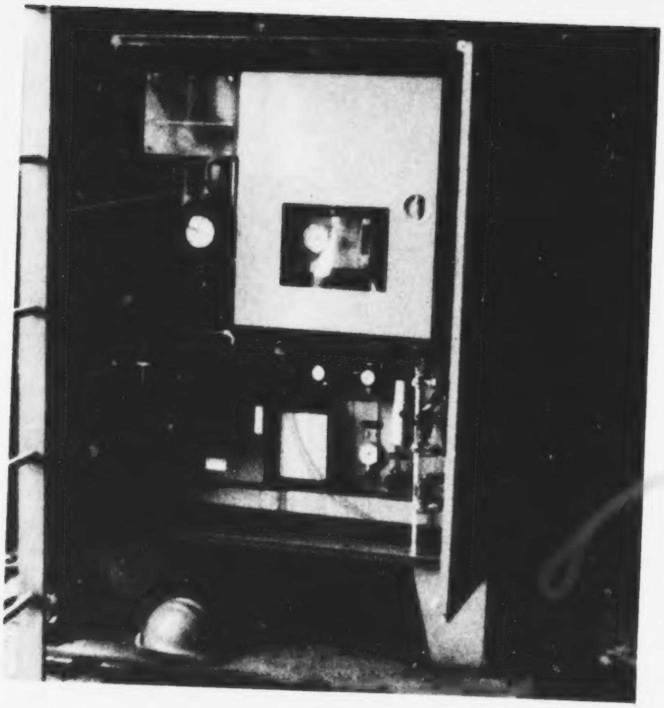


FIGURE 5-9

A DUPONT NDUV ANALYZER AT AN INDUSTRIAL SITE

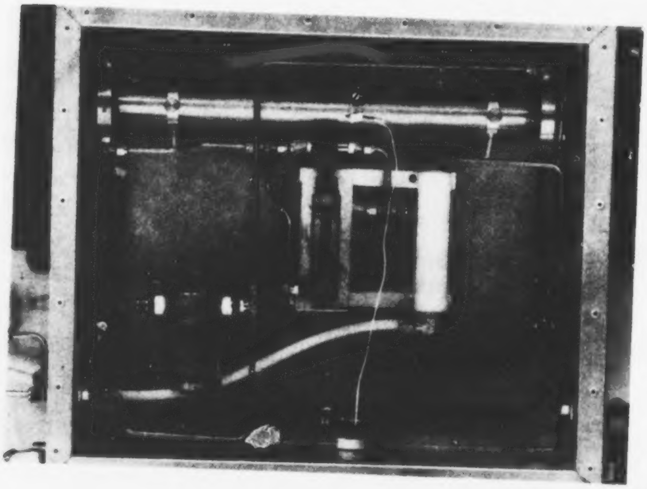


FIGURE 5-10

INTERNAL VIEW OF A DUPONT ANALYZER SHOWING MEASUREMENT CELL AND ASPIRATOR even can be excited to luminescence in a hydrogen flame. These three types of luminescent processes are used in source monitoring applications. Monitors utilizing the effects of luminescence can be very specific for given pollutant species and can have greater sensitivity than some of the absorption or electrochemical methods. Monitors that use each of these luminescent processes will be discussed in this section.

5.2.2.2 Fluorescence Analyzers for SO_2

Fluorescence is a photoluminescent process in which light energy of a given wavelength is absorbed and light energy of a different wavelength is emitted. In this process, the molecule that is excited by the light energy will remain excited for about 10^{-8} to 10^{-4} second. This period of time will be sufficient for the molecule to dissipate some of this energy in the form of vibrational and rotational motions. When the remaining energy is reemitted as light, the energy of the light will be lower, meaning light of a longer wavelength (shorter frequency) will be observed. The fluorescence spectrum for SO_2, shown in Figure 5-11, illustrates this point.

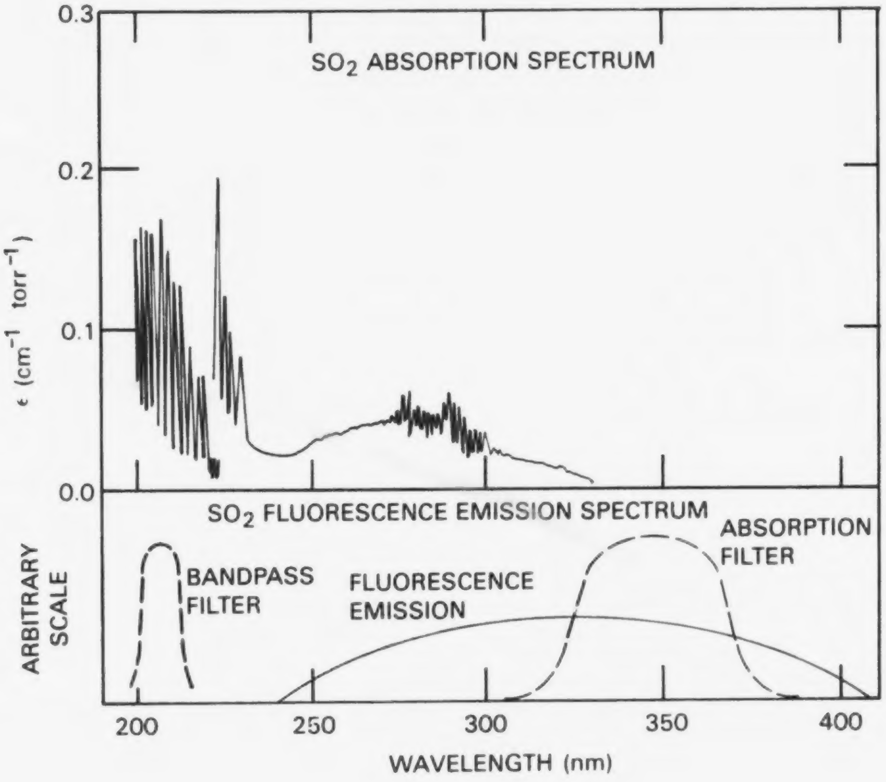


FIGURE 5-11

FLUORESCENCE SPECTRUM OF SO_2

The basis behind the fluorescence technique is to irradiate the molecule with light at a given wavelength (usually in the near ultraviolet) and to measure the emitted light at a longer wavelength.

Commercially available instruments contain either a continuous or a pulsed ultraviolet light source (see Figure 5-12). The light from the source is filtered to a narrow region that is centered near 210 nm in the near ultraviolet range where the SO_2 molecule will be excited. The fluorescent radiation is measured at right angles to the sample chamber with a photomultiplier tube. Another filter is used to select only a portion of the fluorescent radiation for measurement, since interferences can occur over the range of the fluorescence emission spectrum. Figure 5-13 is an internal view of a TECO fluorescence monitor. Fluorescence monitors have been applied successfully to monitoring ambient air. Using these instruments in source monitoring requires attention to the problem of quenching. In the process,

$$SO_2 + h\nu \rightarrow SO_2^* \rightarrow SO_2 + h\nu'$$

The excited SO_2 molecule (SO_2^*) may collide with another molecule before it can release its extra energy as light. The energy, instead, will be lost in the collision and will make the molecules move faster after the collision. Water, CO_2, O_2, N_2, or any other molecule, for that matter, can quench the emission of the radiation. The problem is, however, that each of these molecules has a different quenching efficiency. If one changes the composition of the background gases in a sample, such as having 5 percent O_2 and 10 percent CO_2 in a combustion gas, the SO_2 reading obtained would be different from that obtained if the background gas were ambient air containing 21 percent oxygen. However, it so happens that the quenching effect of CO_2 is approximately the same as that of oxygen. A decrease of oxygen in a flue gas generally means a relative increase in CO_2. The errors due to the differences range from 5 to 10 percent of the SO_2 concentration. The SO_2 values can be corrected by knowing the CO_2 and oxygen percentages by means of a nomograph supplied by the instrument manufacturer.

The SO_2 fluorescence monitors are customarily calibrated using SO_2 in air mixtures. It has often happened that a technician will take a convenient cylinder of span gas having SO_2 in nitrogen instead of in air. Spanning the instrument with such a mixture will cause the subsequent SO_2 readings to be approximately 30 percent lower than the true values. Ideally, the best way to span fluorescence analyzers for source application would be to use a span gas with a composition similar to that of the stack effluent.

Fluorescence monitors, outside of the quenching problem, have no other significant interference problems. Particulates and water must be completely removed from the sampling stream before entering the sampling chamber or the instrument will be easily fouled. Permeation tube dryers (see the following chapter) generally are used in the instrument itself to eliminate any remaining water vapor that is not removed by the extractive system.

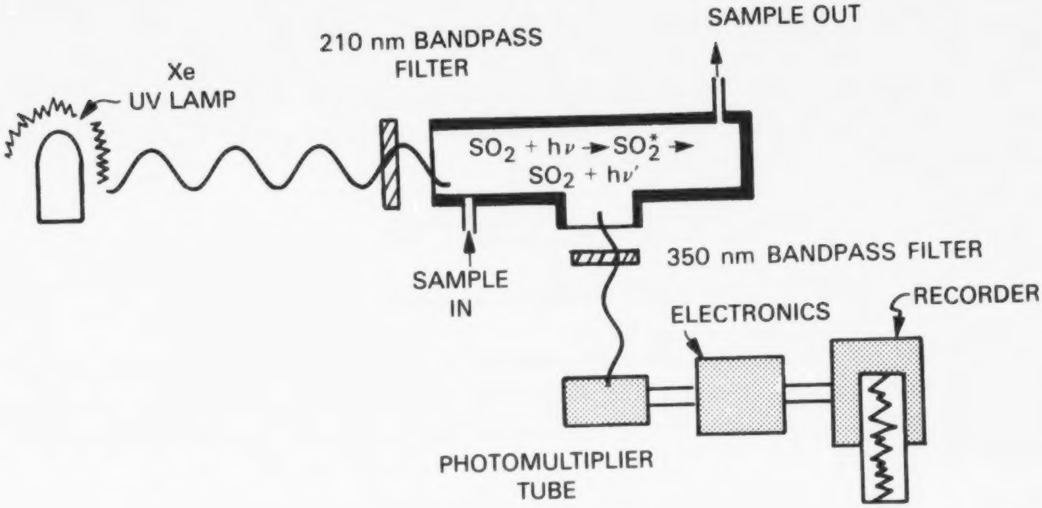

SAMPLE OUT
210 nm BANDPASS FILTER
Xe UV LAMP
$SO_2 + h\nu \rightarrow SO_2^* \rightarrow SO_2 + h\nu'$
SAMPLE IN
350 nm BANDPASS FILTER
ELECTRONICS
RECORDER
PHOTOMULTIPLIER TUBE

FIGURE 5-12

OPERATION OF THE SO_2 FLUORESCENCE ANALYZER

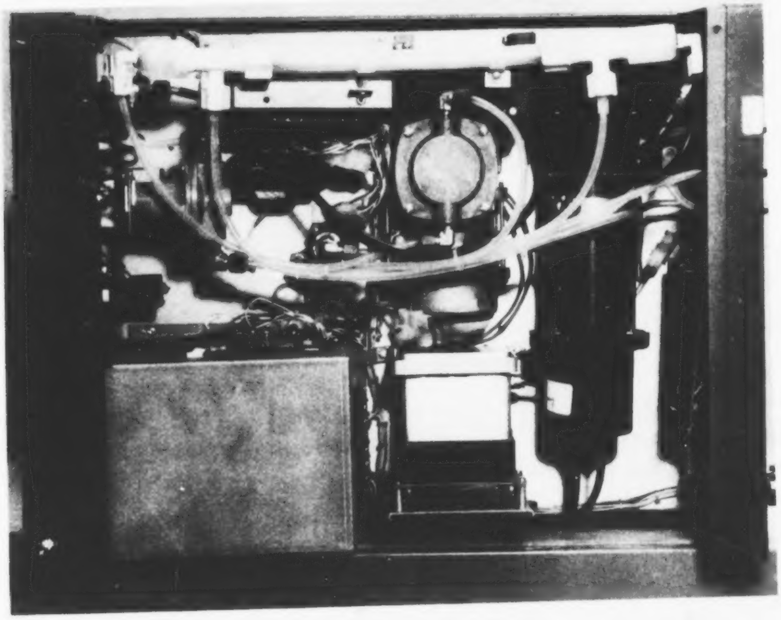


FIGURE 5-13

INTERNAL VIEW OF A TECO FLUORESCENCE MONITOR

5.2.2.3 Chemiluminescence Analyzers for NO_x and NO_2

Chemiluminescence is the emission of light energy that results from a chemical reaction. It was found in the late 1960's that the reaction of NO and ozone, O_3, will produce infrared radiation from about 500 to 3000 nm.

$$NO + O_3 \rightarrow NO_2^* + O_2$$

$$NO_2^* \rightarrow NO_2 + h\nu \text{ (light)}$$

Figure 5-14 shows the emission spectrum observed in this reaction. Monitors that measure NO concentrations by observing the chemiluminescent radiation select only a narrow region of the total emission; a filter is used to select light in the region from about 600 to 900 nm.

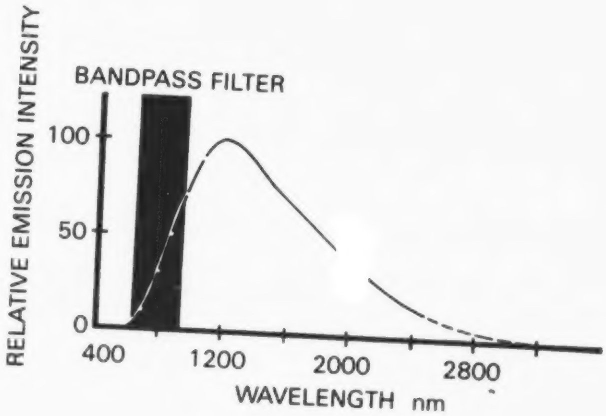


FIGURE 5-14

THE CHEMILUMINESCENT EMISSION SPECTRUM OF NO_2

Nitrogen dioxide (NO_2) does not undergo this reaction and must be reduced to NO before it can be measured by this method. Most commercial analyzers contain a converter that catalytically reduces NO_2 to NO.

$$NO_2 \xrightarrow[\text{Catalyst}]{\text{Heat}} NO + \tfrac{1}{2}O_2$$

The NO produced is then reacted with the ozone and the chemiluminescence measured to give a total NO + NO_2 (NO_x) reading. Figure 5-15 shows a schematic typical of this class of instruments.

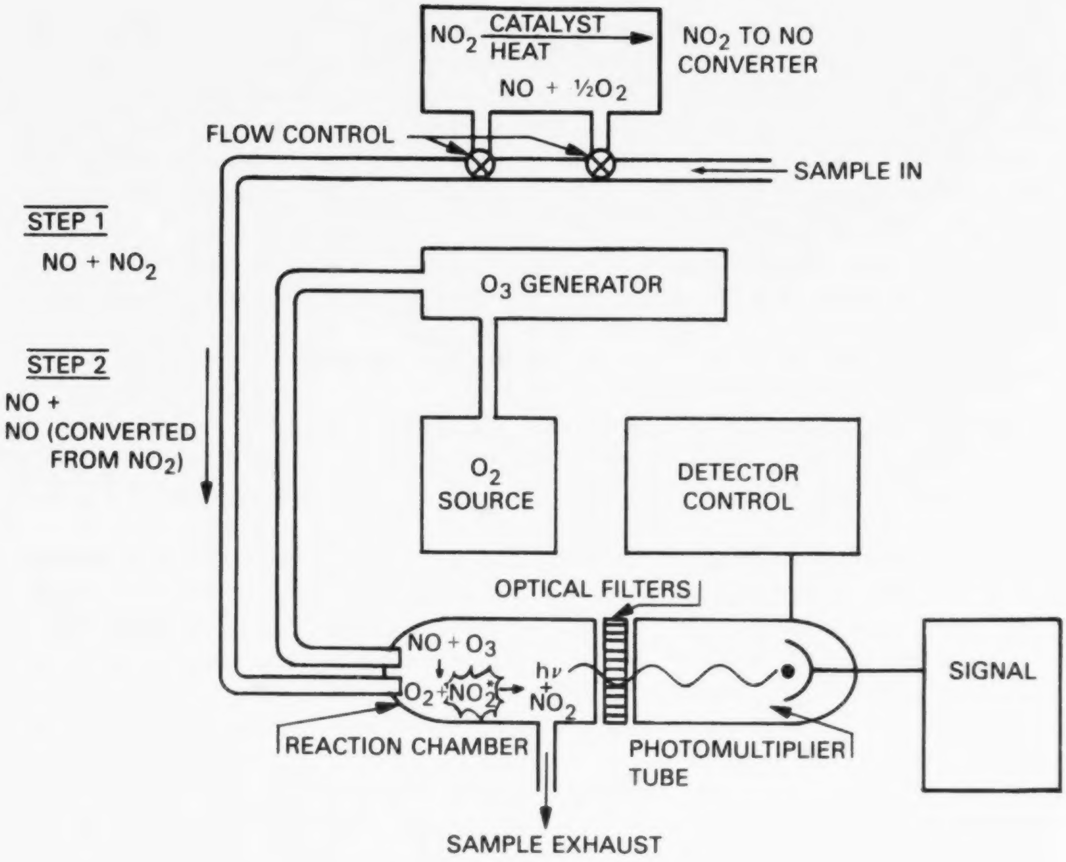

NO2 CATALYST HEAT NO + ½O2
NO2 TO NO CONVERTER
FLOW CONTROL
SAMPLE IN
STEP 1
NO + NO2
STEP 2
NO + NO (CONVERTED FROM NO2)
O3 GENERATOR
O2 SOURCE
DETECTOR CONTROL
OPTICAL FILTERS
NO + O3
O2 + NO2*
hν + NO2
SIGNAL
REACTION CHAMBER
PHOTOMULTIPLIER TUBE
SAMPLE EXHAUST

FIGURE 5-15

OPERATION OF A CHEMILUMINESCENCE ANALYZER

Ozone is generated by the ultraviolet irradiation of oxygen in a quartz tube. The ozone is provided in excess to the reaction chamber to ensure complete reaction and to avoid quenching effects. Since the photomultiplier signal is proportional to the number of NO molecules, not to the NO concentration, the sample flowrate must be carefully controlled. The NO_2 to NO converter chamber is generally made of stainless steel or molybdenum to effect the catalytic decomposition. A few monitors on the market will switch the sample gas automatically in and out of the converter to give almost continuous readings for both NO and NO_2.

The chemiluminescence method has been proven reliable (it is now an approved EPA method for ambient air NO_x analysis). Molecules, such as O_2, N_2, and CO_2, quench the light radiation of this chemiluminescent reaction as in the fluorescence measurement technique. The quenching problem has, however, been uniquely solved by choosing a flowrate of ozone into the sample chamber much greater than that of the sample flowrate. The resulting dilution gives a relatively constant background gas composition and the effects caused by different quenching efficiencies of different molecules are minimized. The only serious interference is ammonia, which will oxidize to NO in stainless steel converter chambers. This is not usually a problem when the monitor is placed on a combustion source, but care should be taken in other applications. Molybdenum converters operated at lower temperatures will not oxidize such nitrogen compounds as ammonia.

5.2.2.4 Flame Photometric Analyzers for Sulfur Compounds

Another luminescence technique used to detect gaseous pollutants is that of flame photometry. Flame photometric analyzers are primarily used in ambient air sampling, but have been applied to stationary source sampling by using sample dilution systems.

Flame photometry is a branch of spectrochemical analysis in which a sample is excited to luminescence by introduction into a flame. Instead of using an ultraviolet or visible light source to excite the SO_2 molecule, as in photoluminescence, a hydrogen flame is used in the flame photometric method to excite the sulfur atom. The excited atom will in turn emit light in a band of wavelengths centered at about 394 nm, which is then detected by a photomultiplier tube, as shown in Figure 5-16. The method is specific to sulfur, not to sulfur dioxide. Compounds, such as H_2S, SO_3, and mercaptans, will contribute to the ultraviolet emission to give a measure of the total sulfur content of the sample stream. With the use of scrubbers or chromatographic techniques, selective determinations could be made of each of these compounds.

A disadvantage of flame photometric analyzers is the required hydrogen for the flame. Facilities that have strict regulations concerning the use of hydrogen and hydrogen cylinders may find it inconvenient to utilize this method. There are currently only a few manufacturers of source-level flame photometric analyzers. The analyzers manufactured by Meloy contain a dilution system within the analyzer. Meloy has recently completed an EPA development contract for an H_2S fuel-gas monitor using this method. The H_2S monitor has proven successful in field experiments and may soon become available commercially from Meloy. An instrument panel of a Meloy analyzer is shown in Figure 5-17.

5.2.3 Extractive Analyzers – Electroanalytical Methods of Analysis

5.2.3.1 General

The instruments discussed in previous sections rely on spectroscopic, electro-optical techniques to monitor particulates and gases. Another class of instruments based upon

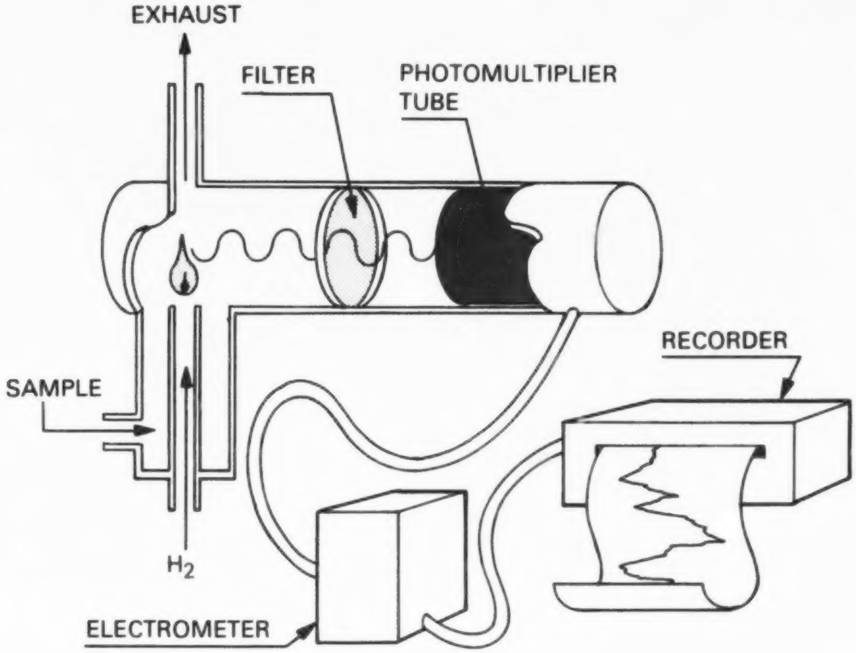


FIGURE 5-16

OPERATION OF A FLAME PHOTOMETRIC ANALYZER

electroanalytical methods of measurement has found great utility in source monitoring applications. There are four distinct types of electroanalytical methods used in source monitoring. These are:

- Polarography
- Electrocatalysis
- Amperometric Analysis
- Conductivity

A number of monitors based on polarographic and electrocatalytic methods are available for source monitoring applications. Polarographic analyzers have been developed for a number of gases and can be inexpensive and portable, ideal for inspection work. Complete continuous source-monitoring systems also are available from manufacturers of these instruments. The electrocatalytic or high temperature fuel-cell method, as it is often called, is used to monitor oxygen only. Both extractive and in-stack monitors are available using this technique. The methods of amperometric analysis and conductivity are less widely used and are subject to a number of interferences. Descriptions of these methods are given here, since a few instruments employing them are still marketed.

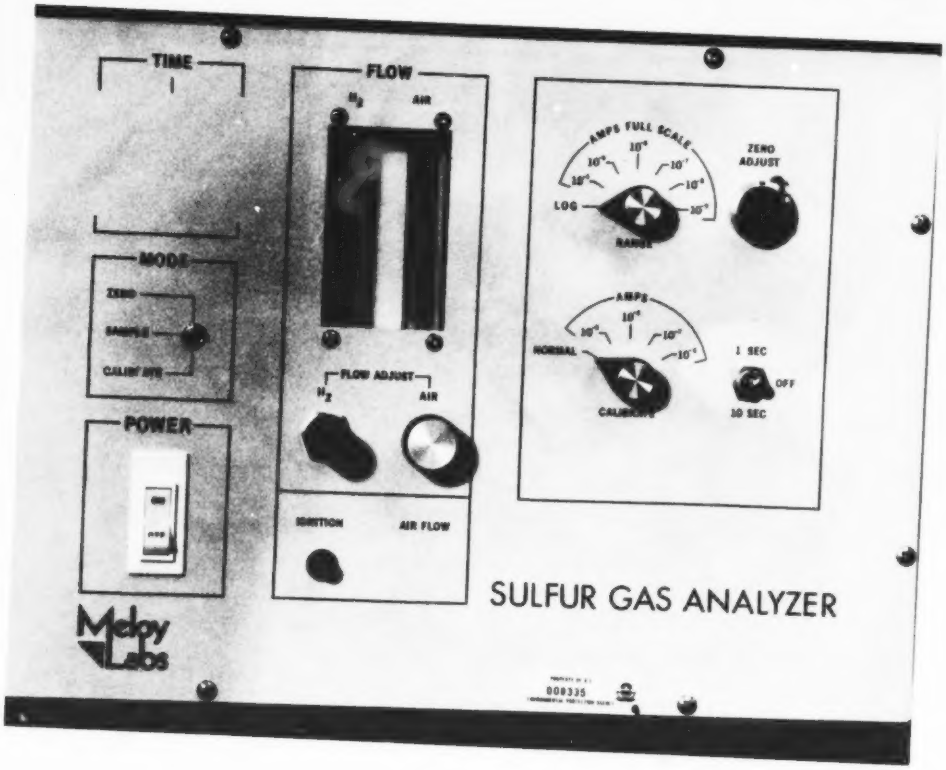

TIME
FLOW
H2
AIR
MODE
ZERO
SAMPLE
CALIBRATE
POWER
FLOW ADJUST
H2
AIR
IGNITION
AIR FLOW
AMPS FULL SCALE
LOG
RANGE
ZERO ADJUST
AMPS
NORMAL
CALIBRATE
1 SEC
OFF
10 SEC
SULFUR GAS ANALYZER
Meloy Labs
000335

FIGURE 5-17

INSTRUMENT PANEL OF A MELOY FLAME PHOTOMETRIC ANALYZER

The principles behind the polarographic and electrocatalytic methods are somewhat more difficult to understand than the spectroscopic principles discussed earlier. A combination of classical electrochemistry and modern fuel-cell technology has provided the theoretical bases for their development. An understanding of the underlying operational principles, however, is important for their evaluation.

5.2.3.2 Polarographic Analyzers

Polarographic analyzers have been called voltammetric analyzers or electrochemical transducers. With the proper choice of electrodes and electrolytes, instruments have been developed utilizing the principles of polarography to monitor SO_2, NO_2, CO, O_2, H_2S, and other gases.

The transducer in these instruments is generally a self-contained electrochemical cell in which a chemical reaction takes place involving the pollutant molecule. Two basic techniques are used in the transducer: 1) the utilization of a selective semipermeable membrane that allows the pollutant molecule to diffuse to an electrolytic solution, and 2) the measurement of the current change produced at an electrode by the oxidation or reduction of the dissolved gas at the electrode. For SO_2, the oxidation that takes place is:

$$SO_2 + 2H_2O \rightarrow SO_4^{-2} + 4H^+ + 2e^- \qquad E^\circ_{298} = 0.17v$$

Figure 5-18 shows a schematic of a typical electrochemical transducer.

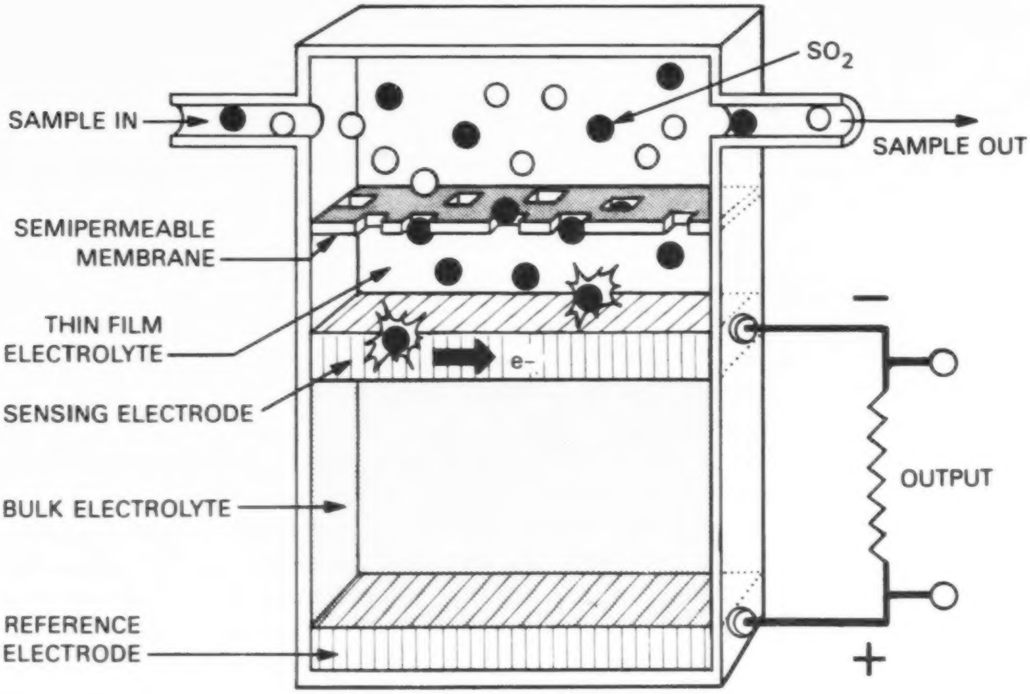

SO_2
SAMPLE IN
SAMPLE OUT
SEMIPERMEABLE MEMBRANE
THIN FILM ELECTROLYTE
SENSING ELECTRODE
e-
BULK ELECTROLYTE
REFERENCE ELECTRODE
−
OUTPUT
+

FIGURE 5-18

OPERATION OF AN ELECTROCHEMICAL TRANSDUCER

The generation of electrons at the sensing electrode produces an electric current that can be measured. There are two reasons why this type of system may be termed polarographic or voltammetric. In typical polarographic analyzers used in chemical laboratories, the electric current in the system is related to the rate of diffusion of the reacting species to the sensing electrode. It turns out that if the rate at which the reactant reaches the sensing electrode is diffusion controlled, the current will be directly proportional to the concentration of reactant. This is known as Fick's law of diffusion:

$$i = \frac{nFADc}{\delta} = kc$$

where:

i = current in amps

n = number of exchanged electrons per mole of pollutant

A = exposed electrode surface area

F = Faraday constant (96,500 coulombs)

D = diffusion coefficient of the gas in the membrane and film

c = concentration of the gas dissolved in the electrolyte layer (moles/μm^3)

δ = thickness of the diffusion layer in cm.

This effect is characteristic of polarographic analyzers.

The other reason why this type of system is termed polarographic is that a retarding potential can be maintained across the electrodes of the system to prevent the oxidation of those species that are not as easily oxidized. There is a difference between the electrochemical transducers used for source monitoring and those used in the chemical laboratory. In the laboratory instruments an external potential is applied to the system until the decomposition potential of a given species is reached and an oxidation-reduction reaction occurs. By varying the potential, both qualitative and quantitative information can be obtained about the composition of a solution. The polarographic analyzers used in source monitoring, however, act much like a battery. The oxidation-reduction reaction occurs at the sensing electrode, because the counterelectrode material has a higher oxidation potential than that of the species being reacted. In the cell, the sensing electrode has a potential equal to that of the counterelectrode minus the iR drop across the resistor. The sensing electrode is electrocatalytic in nature and, being at a high oxidation potential, will cause the oxidation of the pollutant and a consequent release of electrons. This can be seen from the example given in Figure 5-19.

The reaction that takes place at the counterelectrode is:

$$PbO_2 + SO_4^{=} + 4H^+ + 2e^- \rightarrow PbSO_4 + 2H_2O \quad E^\circ_{298} = 1.68v$$

The half-cell potential of 1.68v is in contrast to +0.17v for the oxidation of SO_2 to $SO_4^{=}$. Similar oxidation-reduction reactions occur for different pollutants and electrode electrolyte systems. Figure 5-19 shows that the operation of these systems involves

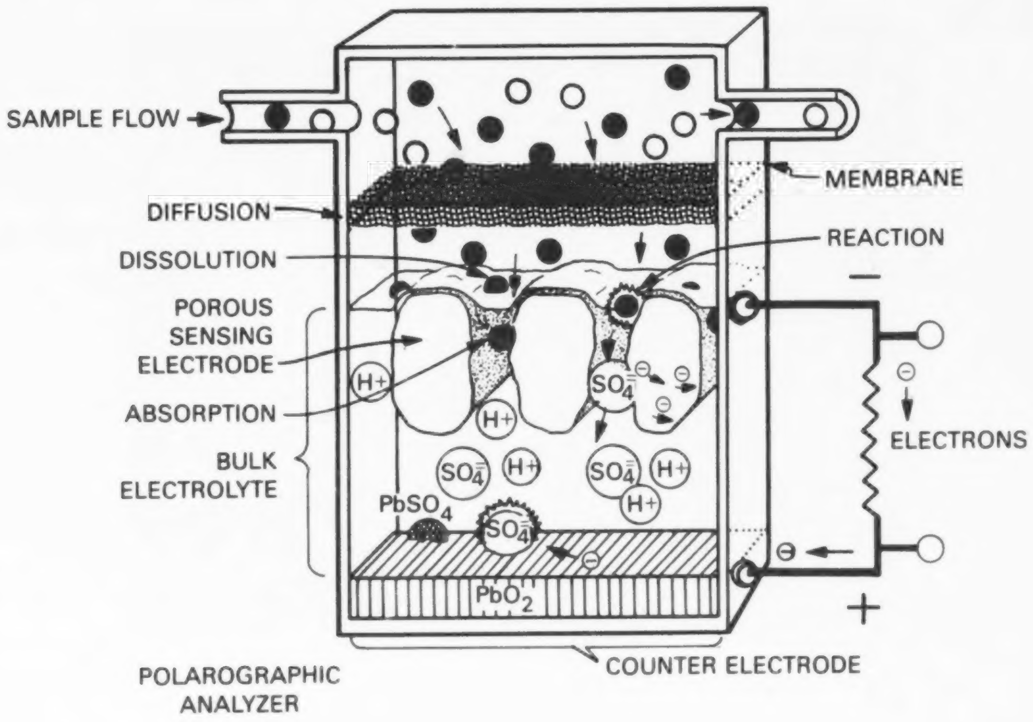

SAMPLE FLOW
MEMBRANE
DIFFUSION
REACTION
DISSOLUTION
POROUS SENSING ELECTRODE
ABSORPTION
BULK ELECTROLYTE
ELECTRONS
H+
SO4=
PbSO4
PbO2
COUNTER ELECTRODE
POLAROGRAPHIC ANALYZER
−
+

FIGURE 5-19

DETAILS OF THE POLAROGRAPHIC PROCESS

1) diffusion of the pollutant gas through the semipermeable membrane, 2) dissolving of the gas molecules in the thin liquid film, 3) diffusion of the gas through the thin liquid film to the sensing electrode, 4) oxidation-reduction at the electrode, 5) transfer of the charge to the counterelectrode, and 6) reaction at the counterelectrode. The electron current through the resistor then can be picked off as a voltage and suitably monitored.

The cells themselves come in a number of configurations, depending upon the manufacturer; various claims are made about the response and selectivity of the instrument related to the cell design. These systems are small and portable and compared to practically all other source monitoring instruments, they are the least expensive. These two factors make them ideal for source inspection, as warning detectors or even as dosimeters. An example of such an inspection system is given in Figure 5-20.

If this method is used for continuous monitoring, a turn-key system should be purchased from the vendor. Figure 5-21 shows an SO_2 alarm monitor developed for industrial application. The vendor will design and build a monitoring system to satisfy a given

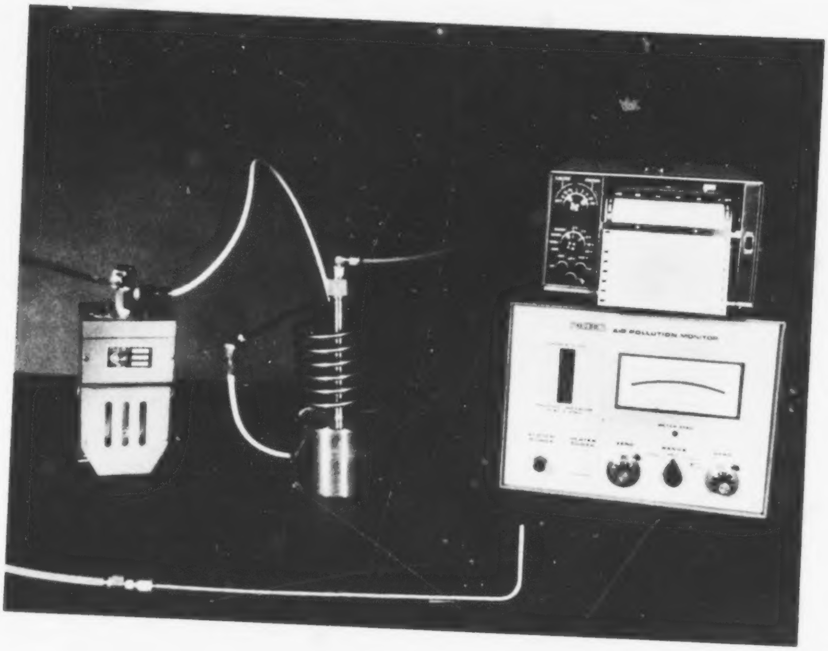


FIGURE 5-20

A PORTABLE INSPECTION SYSTEM USING A POLAROGRAPHIC ANALYZER

need using the experience gained over the many years of developing extractive systems. Attempts by inexperienced technicians to save money by building monitoring systems with inexpensive instruments and components usually result in innumerable problems and often failure.

The polarographic analyzers in their earlier development were temperature sensitive, but temperature compensation devices are now generally provided to avoid this problem. The electrolyte of the cells generally will be used up in 3 to 6 months of continuous use. The cells can be sent back to the company and recharged or new ones can be purchased. It is extremely important that the sample gas be conditioned before entering these analyzers. The stack gas should come to ambient temperature and the particulate matter and water vapor should be removed to avoid fouling the cell membrane.

With proper use, polarographic analyzers can be a valuable tool to an air pollution agency's inspection program or to a source operator wishing to check pollutant levels at various plant locations. Complete systems also are available for continuous monitoring, but should be designed carefully so as to give accurate emission data.

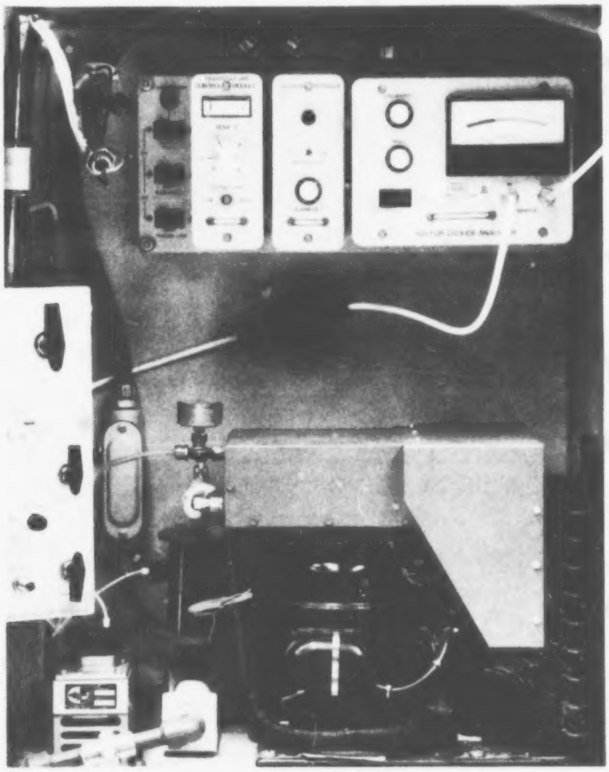


FIGURE 5-21

AN INDUSTRIAL SO_2 "ALARM" MONITOR USING A POLAROGRAPHIC ANALYZER

5.2.3.3 Electrocatalytic Analyzers for Oxygen

A new method for the determination of oxygen has developed over the past several years as an outgrowth of fuel-cell technology. These so-called fuel-cell oxygen analyzers are not actually fuel cells, but simple electrolytic concentration cells that use a special solid catalytic electrolyte to aid the flow of electrons. These analyzers are available in both extractive and in-situ (in-stack) configurations. This versatility of design is making them popular for monitoring diluent oxygen concentrations in combustion sources.

In basic electrochemistry, one of the common phenomena studied is the flow of electrons that can result when two solutions of different concentrations are connected together. As an example, Figure 5-22 reviews this effect.

The electron flow results from the fact that the chemical potential is different on each side and that equilibrium needs to be reached. There are two half-reactions that take place in this example:

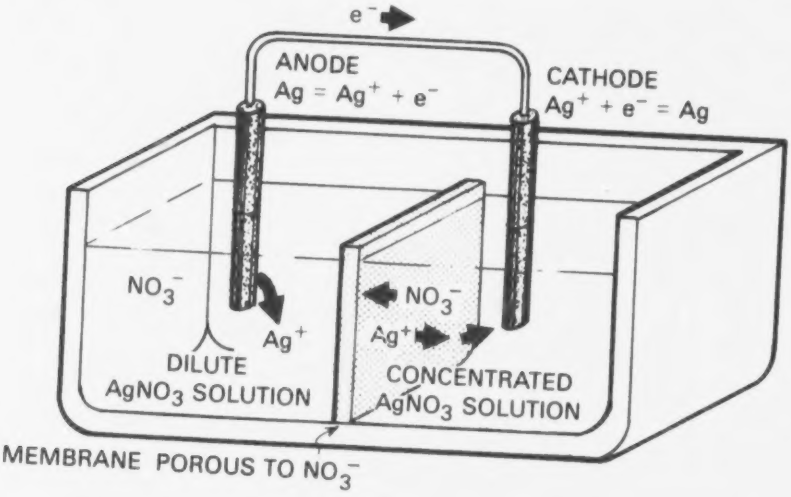

e⁻
ANODE
Ag = Ag⁺ + e⁻
CATHODE
Ag⁺ + e⁻ = Ag
NO3⁻
Ag⁺
DILUTE
AgNO3 SOLUTION
NO3⁻
Ag⁺
CONCENTRATED
AgNO3 SOLUTION
MEMBRANE POROUS TO NO3⁻

FIGURE 5-22

EXAMPLE OF A TYPICAL "CONCENTRATION" ELECTROCHEMICAL CELL

$Ag = Ag^+$ (in dilute solution) $+ e^-$
Ag^+ (in concentrated solution) $+ e^- = Ag$

The tendency for metallic silver to be oxidized to silver ion in a dilute solution of a silver salt is greater than if it were in a concentrated solution. The transfer of electrons effectively results in a transfer of silver ion from a more concentrated to a more dilute solution. In this case, a porous membrane is placed between the two solutions to allow the passage of nitrate ions (NO_3^-) to balance charges. The electromotive force (EMF), or output voltage, that results from a concentration cell is described by the Nernst equation:

$$EMF = \frac{RT}{4F} \ln \frac{c_1}{c_2}$$

where:

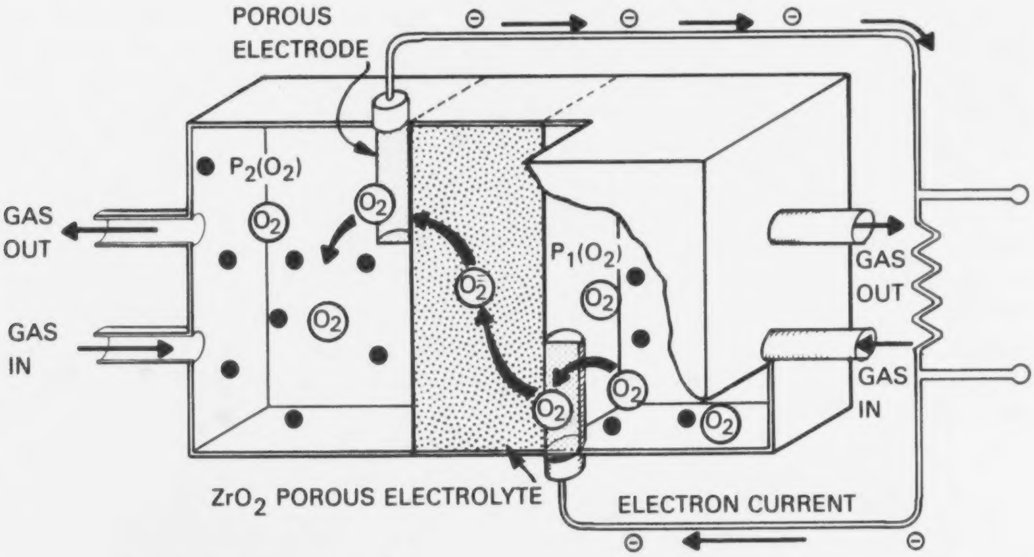
R = gas constant

T = absolute temperature

F = Faraday constant

c_1 and c_2 = concentrations of solutions.

The instruments designed to continuously monitor oxygen concentrations utilize, instead, different concentrations of oxygen gas expressed in terms of partial pressures. A special porous material, zirconium oxide, serves both as an electrolyte and as a high temperature catalyst to produce oxygen ions. A schematic of the electrocatalytic sensing system is shown in Figure 5-23.



$P_{REF}(O2) > P_{SAMPLE}(O2)$

FIGURE 5-23

OPERATION OF AN ELECTROCATALYTIC OXYGEN ANALYZER

When sampling combustion gases, the partial pressure of the oxygen in the sample side will be lower than the partial pressure of oxygen in the reference side, which is generally that of air. When such a cell is kept at a temperature of about 850° C, oxygen molecules on the reference side will pick up electrons at the electrode-electrolyte interface. The porous ceramic material of ZrO_2 has the special property of high conductivity for oxygen ions. This occurs because the metal ions form a perfect crystal lattice in the material, whereas the oxygen ions do not, resulting in vacancies. Heating the zirconium oxide causes the vacancies and oxygen ions to move about. The oxygen ions migrate to the electrode on the sample side of the cell, release electrons to the electrode, and emerge as oxygen molecules. The EMF from this process, expressed in terms of the oxygen partial pressures, is given as

$$\mathrm{EMF} = \frac{RT}{4F} \ln \frac{P_{\mathrm{ref}}(O_2)}{P_{\mathrm{sample}}(O_2)}$$

This EMF can be measured. If the temperature is well stabilized and the partial pressure of the oxygen on the reference side is known, the percentage of oxygen in the sample can be easily obtained.

This phenomenon is used in some high temperature fuel cells. The oxygen analyzers employing this technique, however, do not utilize fuels in the measurement and actually cannot be called fuel cells. One problem with the method is that carbon monoxide, hydrocarbons, and other combustible materials will burn at the operating temperature of the device. This will result in a lowering oxygen concentration in the sample cell, which, however, would be insignificant for concentrations of the combustible materials on the ppm level.

A number of manufacturers are presently marketing oxygen analyzers. Both extractive and in-situ type systems have been developed, providing the source operator with versatility in application. The in-situ system shown in Figure 5-24 employs a ceramic thimble to eliminate particulates from the sample side of the cell. It should be noted that a constant supply of clean dry air for the reference side of the cell is required. Calibration gases can be injected into the measuring cavity contained within the ceramic thimble to check the instrument operation.

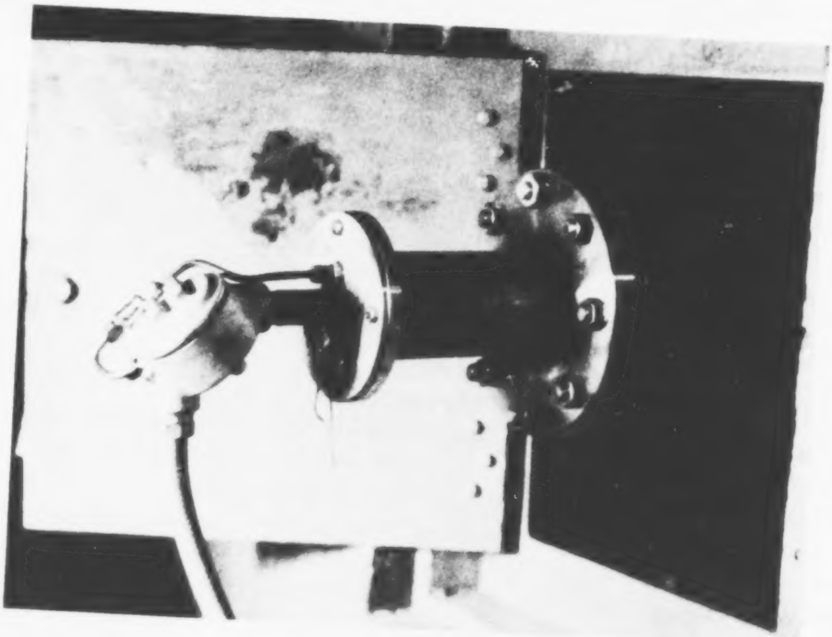


FIGURE 5-24

A LEAR SIEGLER IN-SITU ELECTROCATALYTIC OXYGEN ANALYZER INSTALLED ON A POWER PLANT STACK

5.2.3.4 Amperometric Analyzers

Amperometric analysis is a technique used in a few instruments developed for both ambient and source monitoring. These analyzers (also called coulometric analyzers) measure the number of coulombs required to produce a chemical reaction. Typically, amperometric analyzers measure the current in an electrochemical reaction, such as, $2Br^- \rightarrow Br_2 + 2e^-$. Sulfur dioxide will affect this reaction in the following manner:

$$SO_2 + 2H_2O + Br_2 \rightarrow H_2SO_4 + 2HBr.$$

The instrument measures the change of current flow caused by the change in the rate of Br_2 generation caused by the presence of SO_2. However, amperometric instruments are susceptible to interferences from compounds other than those of interest. Problems with the necessary chemicals and associated plumbing also have made the application of these systems somewhat limited in terms of continuous source monitoring. The technique, however, is useful for the measurement of SO_2, H_2S, and mercaptans.

5.2.3.5 Conductimetric Analyzers

Conductimetric analyzers sense the change in the electrical conductivity in water when a soluble substance is dissolved in it. This change of conductivity is proportional to the concentration of the substance added and can be measured easily. The method, however, is not entirely specific, since both SO_2, NO_x, and acid gases will change the conductivity of water. Interfering gases, therefore, have to be removed before analysis. Calibrated Instruments, Inc. (Mikrogas-MSK), produces a conductimetric analyzer that absorbs SO_2 in a hydrogen peroxide solution.

5.2.4 Extractive Analyzers — Miscellaneous Methods

5.2.4.1 Paramagnetic Analyzers for Oxygen

Molecules will behave in different ways when placed in a magnetic field. This magnetic behavior will be either diamagnetic or paramagnetic. Most materials are diamagnetic and when placed in a magnetic field will be repelled by it. A few materials are paramagnetic; they are attracted by a magnetic field. Paramagnetism arises when a molecule has one or more electrons spinning in the same direction. Most materials will have paired electrons; the same number of electrons spinning counterclockwise as spinning clockwise. Oxygen, however, has two unpaired electrons that spin in the same direction. These two electrons give the oxygen molecule a permanent magnetic moment. When an oxygen molecule is placed near a magnetic field, the molecule is drawn to the field and the magnetic moments of the electrons become aligned with it. This striking phenomenon was first discovered by Faraday and forms the basis of the paramagnetic method for measuring oxygen concentrations.

There are two methods of applying the paramagnetic properties of oxygen in the commercial analyzers. These are the magnetic wind or thermomagnetic methods and the magneto-dynamic methods:

- Magnetic Wind Instruments (Thermomagnetic) – The magnetic wind instruments are based on the principle that paramagnetic attraction of the oxygen molecule decreases as the temperature increases. A typical analyzer utilizes a cross-tube world with filament wire heated to 200°C (see Figure 5-25).

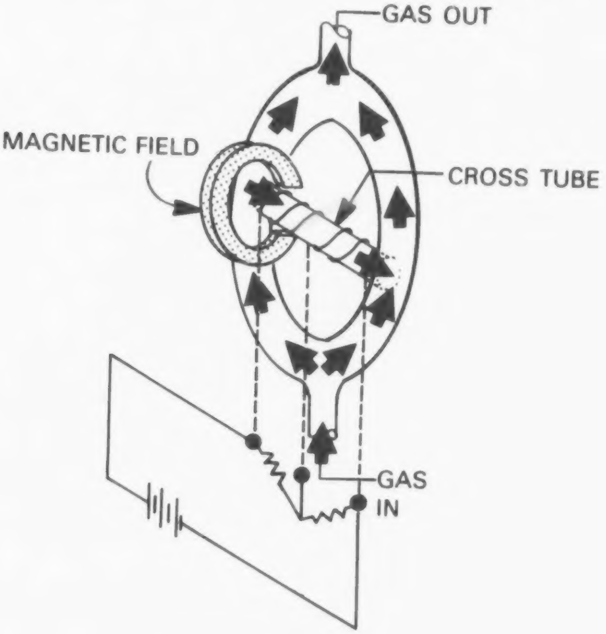


FIGURE 5-25

OPERATION OF A "MAGNETIC WIND" PARAMAGNETIC OXYGEN ANALYZER

A strong magnetic field covers one half of the coil. Oxygen contained in the sample gas will be attracted to the applied field and enter the cross-tube. The oxygen then heats up and its paramagnetic susceptibility is reduced. This heated oxygen will then be pushed out by the colder gas just entering the cross-tube. A wind or flow of gas will therefore continuously pass through the cross-tube. This gas flow will, however, effectively cool the heated filament coil and change its resistance. The change in resistance detected in the Wheatstone bridge circuit can be related to the oxygen concentration.

Several problems can arise in the thermomagnetic method. The cross-tube filament temperature can be affected by changes in the thermal conductivity of the carrier gas. The gas composition should be relatively stable if consistent results are desired. Also, unburned hydrocarbons or other combustible materials may react on the heated filaments and change their resistance.

- Magneto-dynamic Instruments – The magneto-dynamic method utilizes the paramagnetic property of the oxygen molecule by suspending a specially constructed torsion balance in a magnetic field. Here, a dumbbell-shaped platinum ribbon is used. Since platinum is diamagnetic, the dumbbell will be slightly repelled from the magnetic field. When a sample containing oxygen is added, the magnet attracts the oxygen and field lines surrounding the dumbbell are changed. The dumbbell then will swing to realign itself with the new field. Light reflected from a small mirror placed on the dumbbell then can be used to indicate the degree of swing of the dumbbell, and hence, the oxygen concentration.

All of the commercial paramagnetic analyzers are extractive systems. Water and particulate matter have to be removed before the sample enters the monitoring system. It should be noted that NO and NO_2 are also paramagnetic and may cause some interference in the monitoring method if high concentrations are present.

5.2.4.2 Thermal Conductivity Analyzers

Thermal conductivity analyzers operate on the principle that different gases will conduct heat differently. When a sample gas flows over a heated wire, the wire will be cooled and the resistance of the wire will change accordingly. If the composition of the sample gas changes, the cooling rate and the resistance of the wire will change to give an indication of the gas composition. A Wheatstone bridge circuit is generally used to detect the resistance changes in the heated wire.

Thermal conductivity analyzers have been used to monitor CO_2, SO_2, and other gases in process gas streams. A disadvantage to the method is that a flow of reference gas must always be maintained. Changes in the composition of the gas stream other than those due to changes in the pollutant level will interfere in the measurement. Scrubbing systems or some other methods would be necessary in such cases for accurate measurements.

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CHAPTER 6

EXTRACTIVE SYSTEM DESIGN

6.1 Introduction

The discussion of continuous-gaseous emissions monitors up to this point has covered only the measurement principles used in the currently available commercial extractive analyzers. An extractive analyzer cannot provide reliable monitoring data without a properly designed sampling interface. The total extractive system must perform several functions:

- Remove a representative gas sample from the source on a continuous basis.
- Maintain the integrity of the sample during transport to the analyzer (within specified limits).
- Condition the sample to make it compatible with the monitor analytical method.
- Allow a means for a reliable calibration of the system at the sampling interface.

The design of the sampling interface, including the components used in its construction, will depend on the characteristics of both the source gas stream and the monitoring instrument. Emphasis is placed here on the design of the minimum system that will present a minimum capital investment and low operating and maintenance costs.

The procedure recommended for designing an extractive monitoring system includes the following steps:

- Study Federal regulations to determine which pollutant gases must be monitored.
- Review specifications and operating characteristics of several analyzers that could monitor these gases.
- Determine the gas stream parameters at the most feasible sampling sites for the given source.
- Select the best sampling site.
- Select an analyzer most compatible with the sampling site and gas parameters.
- Design a gas sampling interface that will provide the analyzer with a properly conditioned and representative gas stream sample.

This chapter will discuss primarily the information necessary for making evaluations and decisions about sampling interface design.

6.2 Gas Stream Parameters

The gas temperature and velocity profile at all contemplated sampling sites should be determined first. This must be done for any potential sampling site that is not located 8 or more duct diameters downstream of a disturbance to the gas stream. The Federal regulations require that a representative gas sample be extracted. A temperature and velocity profile of the gas stream for locations less than 8 duct diameters downstream of a flow disturbance may give some indication whether or not gas stratification exists.

The particulate loading in the gas stream and the character of the particulates should be evaluated. All extractive systems will require the filtration of particulates from the gas sample stream. The particulate character and loading will affect decisions for coarse and fine filtration systems, sampling pump location in the extractive system, and maintenance scheduling. The reactivity of the particulates toward sulfur dioxide and/or oxides of nitrogen may need to be evaluated (this generally has not been a major consideration; it is worth noting, however). The presence of acid mist and/or water droplets in the gas stream also will effect sampling interface design.*

The water vapor content of the stack gas should be determined. The amount of water vapor present in the stack gas is an important consideration in designing the sample conditioning system for the analyzer. The water vapor content of the stack gas, the analyzer requirements, and sample-gas flowrate are needed to calculate the water removal and drainage needs of the sampling interface. This will assist in making decisions on whether it is necessary to dry the gas stream and on the type of system to use.

The duct absolute pressure may be an important parameter in terms of pump and system valve requirements. It also can be a factor in determining calibration gas injection into the system.

The use of a single analyzer stream to monitor multiple sources requires that all preceding considerations be evaluated for all of the sources to be monitored. It is also necessary to determine the ability of the analyzer to monitor all possible pollutant concentrations from the various sources.

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*Note: Acid mists and/or entrained water droplets are special cases that may require extra care in sampling system design. It is recommended that these situations be discussed with Agency personnel for approval prior to installation.

6.3 Sampling Site Selection

6.3.1 SO_2/NO_x Monitors

Obtaining a representative sample of the pollutant gases is the most important item to consider when selecting a sampling site for an extractive SO_2/NO_x sampling system. The gas sample analyzed must be directly representative or able to be corrected to be representative of the total emissions from the source. A representative sample of the stack gas may be taken at a point where the gases are not stratified. Nonstratified means that the difference between the pollutant gas concentration at any point in the duct more than 1 meter from the duct wall and the average pollutant concentration in the duct is less than 10 percent of the average pollutant concentration. The effluent gases generally are assumed to be nonstratified if the sampling site is located 8 or more duct diameters downstream of any air in-leakage or confluence of different gas streams. This general case does not apply to sampling locations upstream of an air preheater in a steam generating facility.

A sampling location less than 8 duct diameters from air in-leakage must be proven to be consistently representative or corrected to be consistently representative of the total emissions from the facility. It must be shown that the point of average pollutant gas concentration does not shift with changes in the operation of the facility. As a result, a gas concentration profile study is essential for sampling locations being considered for continuous monitoring applications which do not satisfy the 8 duct-diameter criterion.

6.3.2 O_2/CO_2 Monitors

An O_2/CO_2 monitor is used to convert continuous monitoring pollutant concentration data to units of the applicable standard. The O_2/CO_2 monitor must, therefore, be located at a point where measurements can be made that are representative of the pollutant gases sampled by the SO_2/NO_x monitor(s). The O_2/CO_2 monitor sampling point location conforms best with this requirement when it is at approximately the same point in the duct as the SO_2/NO_x system. The O_2/CO_2 gas sample may be extracted from a different duct location if the stack gas is nonstratified at both locations and there is no air in-leakage between the two sampling points. If the O_2/CO_2 monitor sampling point is at a different location from the SO_2/NO_x sample point and stratification exists in that duct, a multipoint extractive probe must be used for sampling. This is also true for the extractive monitoring system when the O_2/CO_2 and SO_2/NO_x monitors are not of the same type (i.e., one is extractive and the other in-situ).

6.3.3 General Comments

The final sampling site selected for continuous monitoring applications must meet the guidelines given in the Federal Register. Several other factors for installation of the extractive sampling interface also must be considered. These include accessibility to the monitor and the interface, system response time, and overall system design.

The sampling site should be easily accessible to plant personnel. A continuous monitor and the sampling interface will need maintenance and calibration by the plant. All components of the system should be as accessible as circumstances will permit. The monitor should be located near the sampling site. This may mean constructing a housing for the monitor to protect it from the environment. The plant may find such an arrangement inconvenient, choosing instead to put the monitor in the plant control room with the sampling interface extended to supply the monitor with the gas sample. The response time of the system for long sampling interface connections must then be considered. An analyzer placed in a control room, away from the sampling site, may require a slightly more complex extractive system. This situation is not prohibitive in cost or operation and may be the best arrangement for a given operation.

The final site selection requires an evaluation of all aspects of accessibility, maintenance, response time, convenience, and gathering of representative data. The decision may involve some trade-offs.

6.4 Analyzer(s) Selection

The analyzer selected for continuous monitoring must be compatible with the source characteristics, sampling site, intended location for installation, and sampling interface. The engineer involved in installing the continuous monitoring system and having performed an examination of gas stream characteristics and site location will now have a basis for choosing the analyzer best suited for the source. The requirements of the analyzer and source gas parameters then will determine the design of the sampling interface.

6.5 Design of the Sampling Interface

6.5.1 General

The design of a sampling interface requires that the system deliver a conditioned, continuous gas sample to the gas analyzer. A number of different interface designs may be able to perform this task at a given source. The actual system designed for a specific source generally will incorporate a variety of trade-offs based on source/analyzer requirements and financial restraints. A system typically will include the following components:

- In-stack sampling probe
- Coarse in-stack filter
- Gas transport tubing
- Sampling pump
- Moisture removal system

- Fine filter
- Analyzer
- Calibration system
- Data recorder

6.5.2 Sampling Probe

Representative gas sampling requires samples that will demonstrate the total pollutant gas emissions from a source. The temperature and velocity traverse across the duct may indicate a necessity for a multipoint probe to extract samples from numerous points across the entire duct. Several research studies have shown that although gas concentration cannot be assumed to correspond directly to temperature and velocity gradients in a duct, these measurements are excellent indications for positioning gas sampling probes. This research has shown that a representative gas sample may be extracted from a grid of equal areas laid out in the duct. A temperature and velocity traverse is then performed in each row of the grid. The multipoint gas sampling probe is then positioned across the row that indicated temperature and velocity readings closest to the average reading in the duct.

Gas sampling requires that particulates, which can harm the analyzer and shorten the operating life of the sample pump, be removed from the gas stream. Directing the probe inlet counter current to the gas flow helps prevent many large particulates from entering the system. Particulates that enter the probe can be removed by coarse and fine filters.

6.5.3 Coarse Filters

The coarse filter should be located at the probe tip in the stack, where it then can prevent particulate matter from plugging the sampling probe and will not require heat tracing to prevent moisture condensation. There are two general types of coarse in-stack filters: external or internal.

The external coarse filter is a porous cylinder (see Figures 6-1 and 6-2). The cylinder is typically constructed of sintered 316 stainless steel, though it may also be glass, ceramic, or quartz. It is essential that the porous cylinder be protected by a baffle to prevent excessive particulate buildup on the leading edges. These porous cylinders have an expected utility of approximately 2 to 3 months before they become clogged with particulate, depending on the sampling rate. Although they can be regenerated by back flushing, they will eventually need replacement. The nominal cost (~$25) suggests that it may be easier to replace the filter on a routine basis rather than install costly automatic back-flushing equipment.

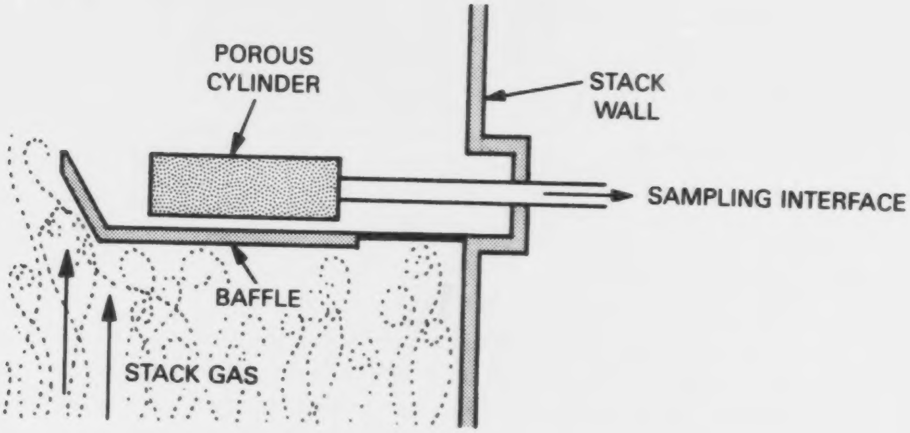

FIGURE 6-1

POROUS CYLINDER USED AS EXTERNAL COARSE FILTER

FIGURE 6-2

ACTUAL POROUS CYLINDER INSTALLED IN A STACK GAS STREAM

The internal filter is housed within a tube (Figure 6-3). The gas enters a probe nozzle, passes through the filter, and proceeds into the sampling interface.

Filter material is available from a number of manufacturers. It has been shown experimentally that a Western Precipitation Alundum thimble permits high particulate loading with a minimal pressure drop. Other filters and filter holders have lower particulate loading capacities. Glass wool filters have been used in some experiments; however, they have a higher pressure drop than the Alundum thimble. The internal filter arrangement is preferred because it allows easier injection of calibration gases (see pump configurations).

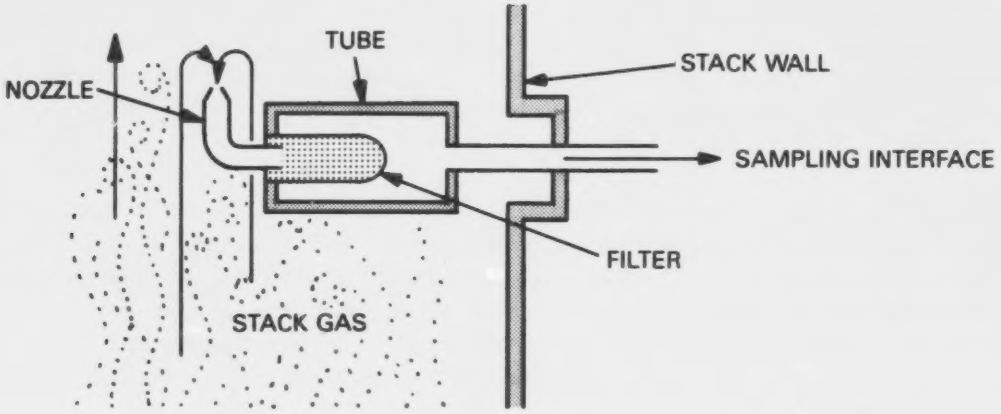
TUBE
NOZZLE
STACK WALL
SAMPLING INTERFACE
FILTER
STACK GAS

FIGURE 6-3

INTERNAL COARSE FILTER

6.5.4 Fine Filters

The majority of extractive stack gas analyzers require almost complete removal of all particles larger than 1 micron from the gas stream. This is best accomplished by including a fine filter near the analyzer inlet. Fine filters are divided into two broad categories: surface filters and depth filters.

Surface filters remove particulates from the gas stream using a porous matrix (Figure 6-4). The pores prevent penetration of particulates through the filter, collecting them on the

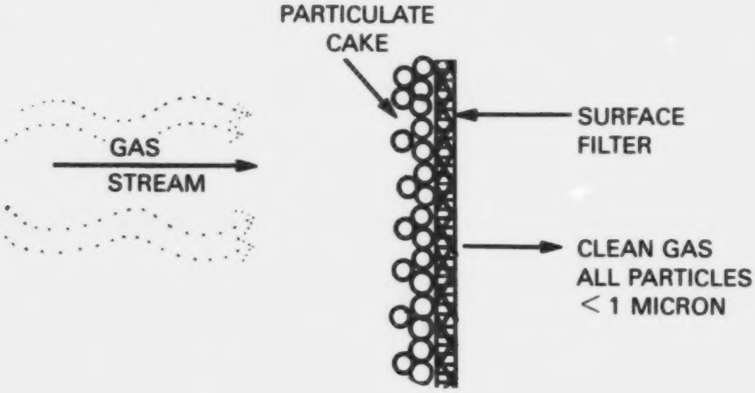
PARTICULATE CAKE
GAS STREAM
SURFACE FILTER
CLEAN GAS ALL PARTICLES < 1 MICRON

FIGURE 6-4

SURFACE FILTER

surface of the filter element. Surface filters can remove particulates smaller than the actual filter pore size with particulate cake buildup and electrostatic forces acting to trap smaller particles. These filters perform well on dry, solid particulates without excessive pressure drop. A surface filter will foul quickly if it becomes wet or if the particulate is gummy.

Depth filters collect particulates within the bulk of the filter material. A depth filter may consist of loosely packed fibers or relatively large diameter granules (Figure 6-5). These filters perform well for gummy solids or moist gas streams and dry solids. In the case of malfunction, their flexibility can protect the analyzer from damage. Glass wool packed to a density of 0.1 gm/cm^3 and a bed depth of at least 2 inches can act as an inexpensive depth filter for normal gas flowrates. These filters must be carefully packed to avoid channeling.

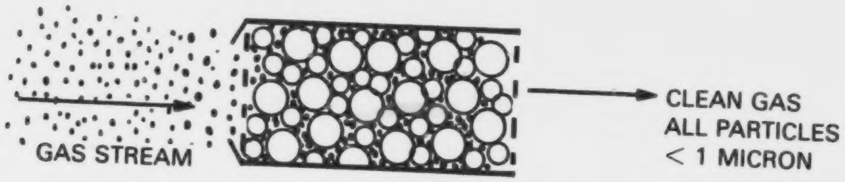

FIGURE 6-5

DEPTH FILTER

6.5.5 Gas Transport Tubing

The gas tubing or sample lines transport the extracted gas sample from the stack through the interface system and into the analyzer. When selecting sampling lines, it is important to consider:

- Tube interior-exterior diameter
- Corrosion resistance
- Heat resistance (for lines near high temperature areas or heat tracing)
- Chemical resistance to gases being sampled
- Cost

The gas tubing must be sized to ensure an adequate gas flowrate with a reasonable pressure drop and good system response time. A flowrate of 2 standard liters per minute (enough to supply two gas analyzers) through a 6.35-mm OD (1/4 inch) tubing exhibits a pressure drop between 1 and 3 mm Hg per 30.48-meter length. This pressure drop is quite acceptable for most sampling pumps. The response time (t) for a sampling line volume (V) can be calculated at a flowrate (F) in the equation:

$$t = \frac{V}{F} \text{ (assuming no axial dispersion or wall effects)}$$

At a flowrate of 1 standard liter minute, the response time for a 30.48-meter tube section at 25° C and pressure drop of 152 mm Hg is only 30 seconds. These data indicate that 6.35-mm OD tubing is acceptable for sampling lines.

Teflon® and stainless steel exhibit excellent corrosion and heat resistance in addition to being chemically inert to stack gases and acid mist. The corrosion resistance of stainless steel is enhanced by keeping gases above the dew point. These materials are commercially available in heat traced form. Teflon® is recommended for out-of-stack heat traced lines; stainless steel is a good material for in-stack lines. Polypropylene and polyethylene lines exhibit good chemical resistance (except to nitric acid). Plastic lines are a good, economical choice for sampling lines that carry dry gas and are maintained above the freezing point without heat tracing. A reliable, effective, and economical sampling line system probably would incorporate stainless steel, Teflon®, and plastic.

6.5.6 Sampling Pump

A diaphragm or bellows pump upstream of the analyzer is superior to other pump types for gas handling. The primary advantages offered are:

- No shaft seal is required; these pumps are not subject to seal failure air in-leakage.
- No internal lubrication is required.
- These pumps are relatively inexpensive.
- Adequate suction and discharge pressures are developed at flowrates well above those needed for gas sampling systems.

A pump positioned upstream of an analyzer may be located in either position A (see Figures 6-6 and 6-7) or B (see Figures 6-8 and 6-9).

There are operational trade-offs that must be considered. The pump positioned in A of this portable system offers the highest condensate removal potential (based on the mole fraction of water vapor being equal to its partial pressure divided by the total pressure at condenser temperature). Pump position A also minimizes the chances of air leakage and allows the use of a simple ball-float trap for water removal from a condenser trap. It also allows the analyzer to operate at pressures and temperatures below those which would occur using pump position B. Pump position B protects the pump from moisture and particulates. This extends pump life and may be an overriding advantage for this position.

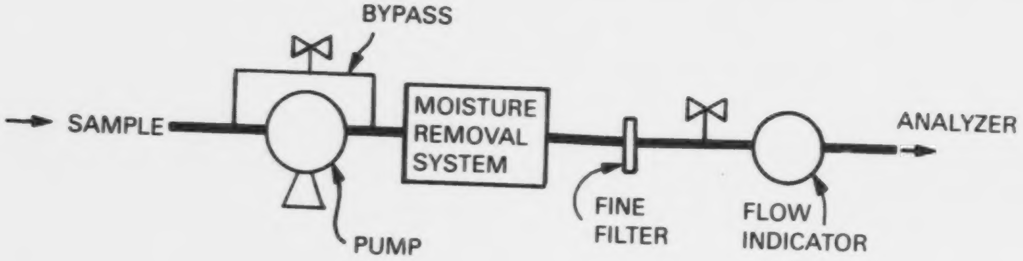
BYPASS
SAMPLE
MOISTURE REMOVAL SYSTEM
ANALYZER
FINE FILTER
FLOW INDICATOR
PUMP

FIGURE 6-6

SCHEMATIC OF PUMP PLACEMENT — POSITION A

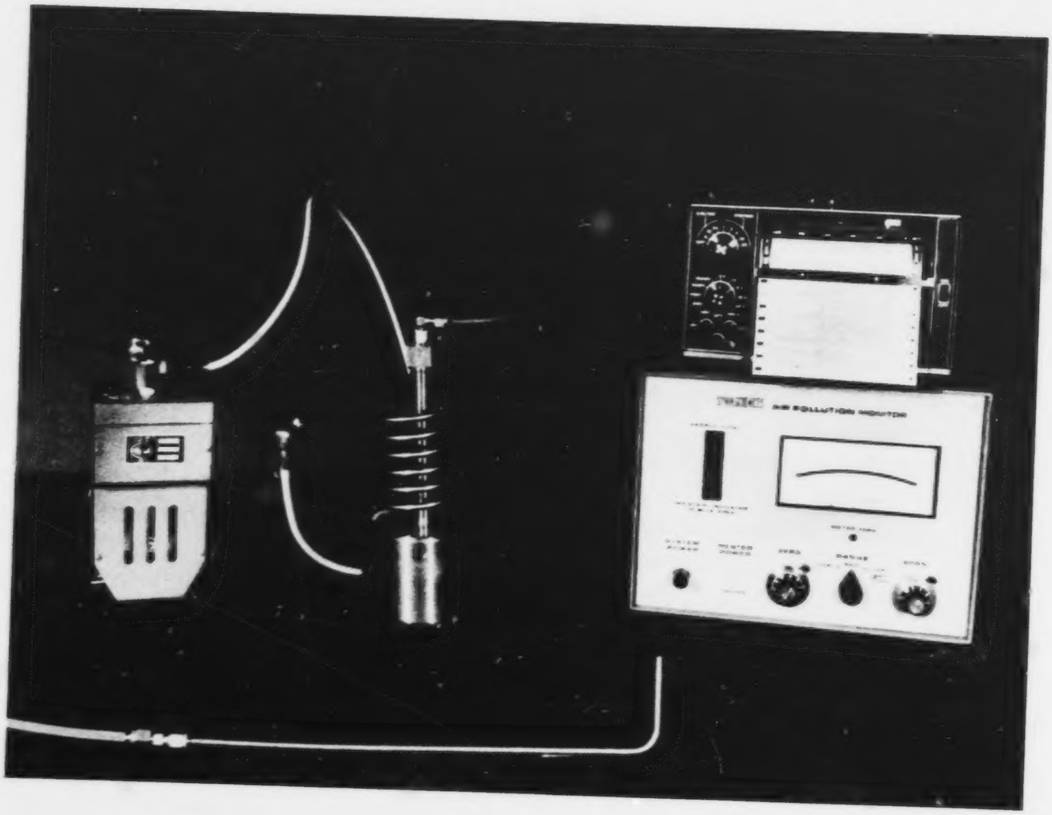
AIR POLLUTION MONITOR

FIGURE 6-7

ACTUAL SAMPLING SYSTEM WITH PUMP IN POSITION A

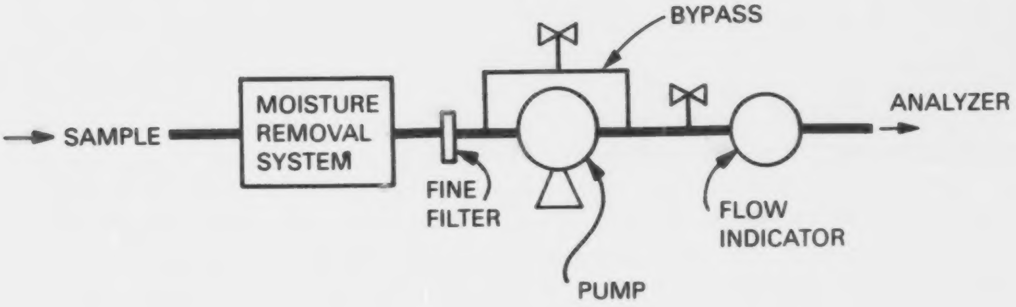

FIGURE 6-8

SCHEMATIC OF PUMP PLACEMENT — POSITION B

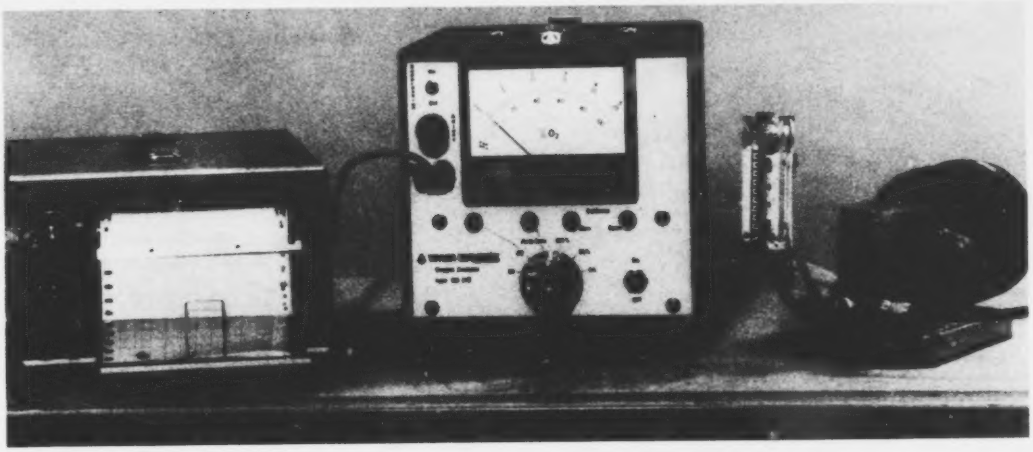

FIGURE 6-9

ACTUAL SAMPLING SYSTEM WITH POSITION B PUMP LOCATION

The diagrams for positions A and B both show a bypass system which connects pump suction and discharge to protect the pump from excessive wear when operated at low flowrates. A pump throttled down for low flow produces a high pressure drop across the pump which can greatly reduce its expected life span.

Some sampling interface systems may place the pump downstream of the analyzer, pulling the sample through the system. This could allow the use of an aspirator pump without moving parts. Pressure drop at the analyzer would be higher, but for some analyzers with built-in pressure regulators, this may be a preferrable arrangement. Downstream pumps increase the potential for air leaking in and, in the case of aspirator pumps, require a source of large quantities of compressed air, steam, or water.

6.5.7 Moisture Removal

Stack gases may contain significant quantities of water vapor. A limited number of analyzers are not affected by the presence of water vapor in the sample (e.g., a differential absorption ultraviolet instrument). These analyzers do, however, require that gases be kept above the dew point to protect against condensation and corrosion within the analyzer. Other analytical methods that are affected by water vapor require moisture removal. Generally, the gas is dried to a low constant level of moisture content for both stack gases and calibration gases. Refrigerated condenser traps or permeation dryers are commonly used for moisture removal.

A refrigerated condenser receives the hot stack gases, then rapidly cools the gas to drop out moisture (Figures 6-10 and 6-11). The refrigerated condenser must provide enough cold surface area to remove the latent heat of vaporization and to cool the gas stream within a minimum residence time in the condenser. This greatly reduces the possibility of pollutant gas absorption in the condensate. The cooling requirements for the condenser are directly

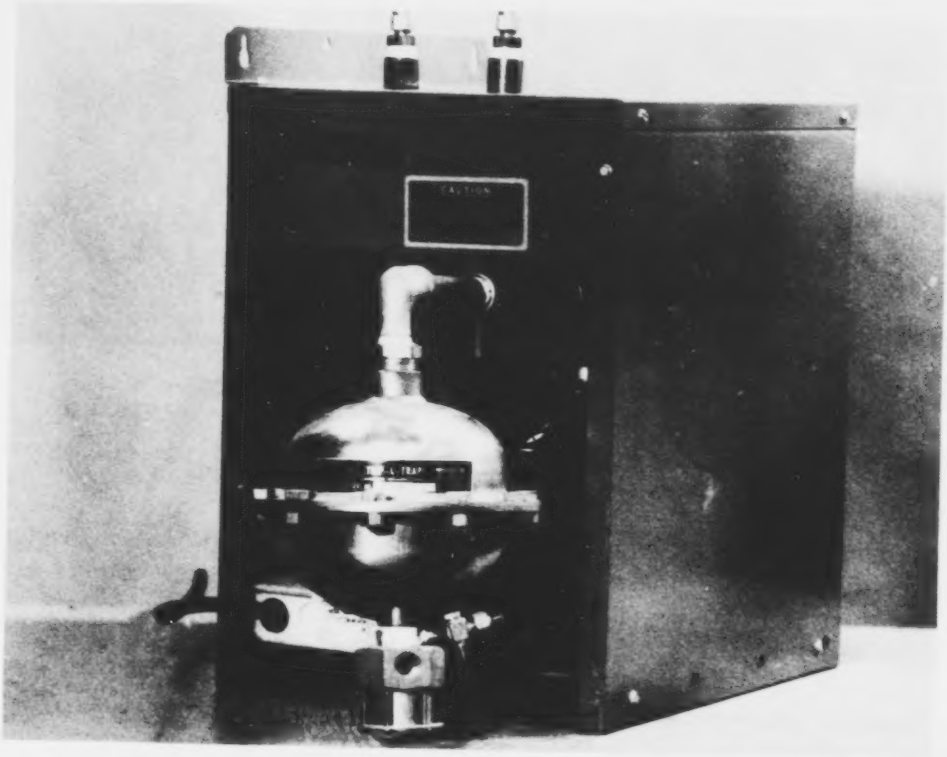

FIGURE 6-10

A REFRIGERATED CHILLER MANUFACTURED BY HANKINSON

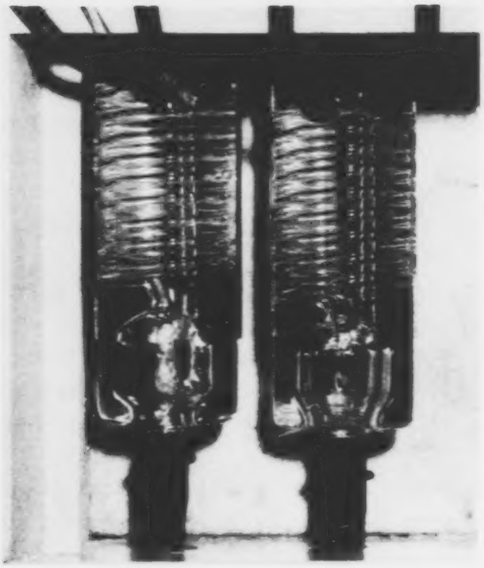

FIGURE 6-11

INTERIOR OF TYPICAL CONDENSER USED FOR MOISTURE REMOVAL

proportional to the gas flowrate. Cooling requirement calculations probably will be made by the manufacturer for use by the condenser purchaser; however, calculations and procedures are given in the literature.

The moisture dropped out of the gas stream must be trapped and removed periodically. This may be done by automatic valving or manual drainage. The amount of water collected over time at the analyzer flowrate (assume 100 percent removal) should be calculated in order to decide on whether or not an automatic system is necessary. The approximate water trapped may be calculated by

$$V_{LC} = \frac{F\ (H_V)}{K} \times 60$$

where:

V_{LC} = milliters of water collected per hour

F = flowrate (standard liters/minute)

H_V = percent water vapor by volume in stack gas

K = a constant = 1.333 liters water vapor/ml at standard conditions

For example, at a source that contains 16 percent water vapor by volume with an analyzer flowrate of 2 standard liters/minute, approximately 15 ml of water would be collected per hour. This could allow manual drainage of the condensate trap on a weekly basis. Normal drainage may be neglected, which makes an automatic system preferrable. Simple suggestions for automatic drainage include a ball-float valve, automatic-timed drain valve, or barometric leg. The drain employed will depend on the pump position. Special care must be made to ensure no air leaking in during trap drainage.

The permeation dryer (Figures 6-12 and 6-13) offers an interesting alternative to the refrigerated condenser. It operates by passing wet stack gases through a tube-shell arrangement in which the tubes are ion-exchange membranes selective for water vapor only. The driving force for the exchange is provided by either evacuating the shell side of the dryer or by back-purging with dry air (which may be taken from tube exit).

The permeation dryer requires that water be held above the dew point entering the dryer and for the first 15 cm of dryer length. It offers the following advantages:

- Less prone to corrosion – no materials contact with wet gases
- No possibility of sample loss in condensate
- No condensate trap required
- Competitively priced

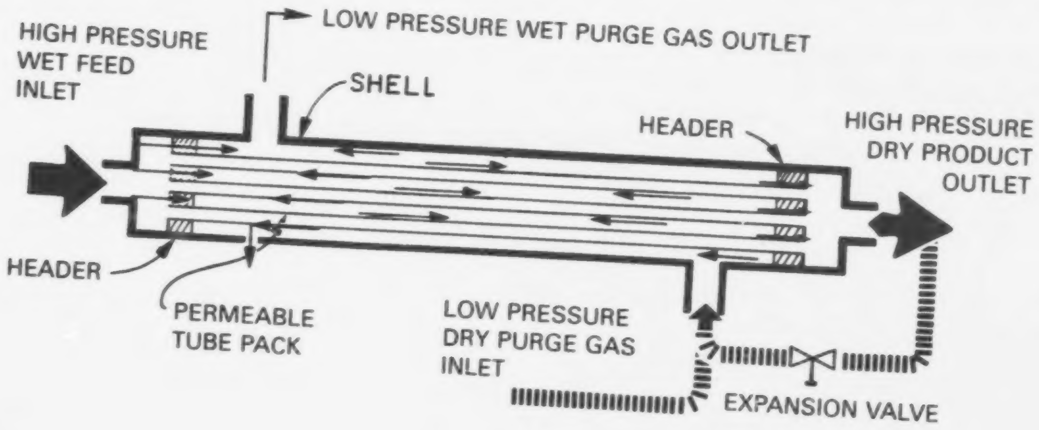
HIGH PRESSURE WET FEED INLET
LOW PRESSURE WET PURGE GAS OUTLET
SHELL
HEADER
HIGH PRESSURE DRY PRODUCT OUTLET
HEADER
PERMEABLE TUBE PACK
LOW PRESSURE DRY PURGE GAS INLET
EXPANSION VALVE

FIGURE 6-12

SCHEMATIC DIAGRAM OF PERMEATION DRYER

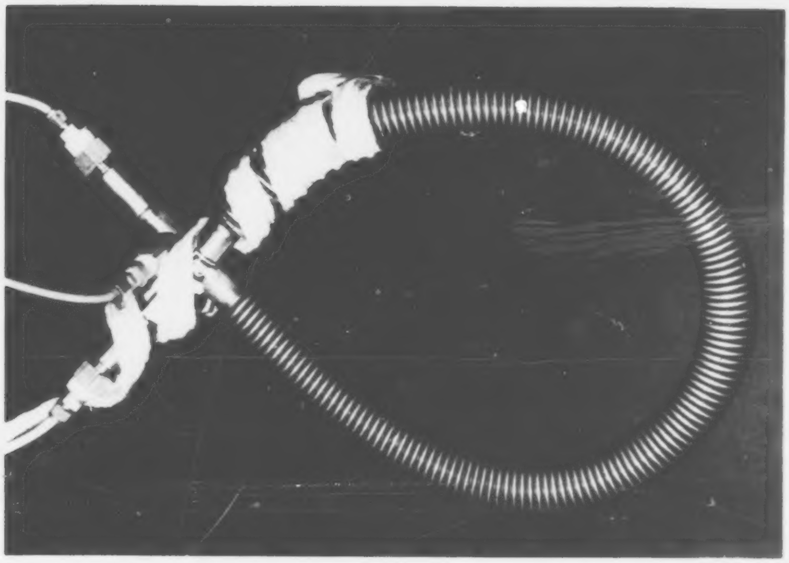

FIGURE 6-13

CORRUGATED STAINLESS STEEL ENCLOSED PERMEATION TUBE DRYER

6.5.8 Sampling Interface/Monitor Calibration

The entire sampling interface and monitor must be calibrated as a unit. The calibration gases should enter the continuous gas monitoring system as near as possible to the same entrance point for the stack gas. This is essential to check the entire system. The analyzer should be calibrated at the same gas flowrate, pressure, temperature, and operating procedure used in monitoring the stack gas. Flooding the coarse filter with calibration gas at the probe inlet or using a check valve that allows calibration gas injection directly behind the coarse filter are the best methods for accomplishing this calibration. Calibration in this manner assures that any leaks, blockage, or sorption of gases taking place in the system will be discovered. The importance of this method cannot be overemphasized. Automatic gas injection systems are easily constructed with electric solenoid valves.

The calibration gases must be checked with triplicate runs of the reference method procedure for that gas. All runs of the reference method must agree with the average for the three runs within 20 percent or they must be repeated. The gas analysis should be repeated every 6 months. Although many manufacturers certify a longer shelf life, experience has shown that manufacturer calibration gas certification is subject to error.

EPA is currently studying the option of using National Bureau of Standards (NBS) calibration gases or gases traceable to NBS standards, instead of requiring reference method analyses. NBS gases are relatively accurate and stable but are more expensive than commercial gases.

6.5.9 Dilution Systems

Several gas dilution systems are commercially available (Meloy, Thermoelectron, Hastings). These systems dilute the stack gas sample with known volumes of inert carrier gas. This reduces gas-handling problems by decreasing the temperature and moisture content of the gas entering the analyzer. A dilution system is useful in adapting ambient air instruments to source monitoring applications. These dilution systems may add unnecessary complexity to the sampling system, increasing initial costs and maintenance costs in addition to slowing system response time. The inherent problems involved in maintaining precise dilution ratios also may reduce the overall measurement accuracy.

6.5.10 Controlling the Sampling Interface/Monitor System

The best system does not require elaborate control mechanisms. The necessary controls are easily installed and maintained by plant personnel. The suggested controls include the following:

- Temperature control at the cold end of the heated sample line. This is to ensure that the gases are above freezing to protect the lines from fracture or blocking. Temperature should also be controlled at the refrigerated condenser to maintain moisture removal efficiency.

- Pressure control is needed at the pump discharge to protect the pump. The pressure drop across the fine filter should be monitored to protect the analyzer and to ensure proper system function (most analyzers are sensitive to pressure changes).

- Gas flowrate control should be installed to make certain the analyzer receives the correct gas flow. This is not critical, since most analyzers are relatively insensitive to minor flowrate change.

- Calibration gas valving should automatically inject calibration gases once every 24 hours. This can be accomplished with a simple electric solenoid valve. The calibration gases should flow through the sampling system at the same condition of temperature, pressure, and flow as does the stack gas.

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CHAPTER 7

IN-SITU MONITORING SYSTEMS

7.1 Introduction

The problems and expense associated with extractive monitoring systems have led to the development of instrumentation that can directly measure source-level gas concentrations in the stack. The so-called in-situ systems do not modify the flue gas composition and are designed to detect gas concentrations in the presence of particulate matter. Since particulate matter causes a reduction in light transmission, in-situ monitors utilize advanced electro-optical techniques to eliminate this effect when detecting gases. These techniques are:

Differential Absorption	Gas Filter Correlation	Second Derivative Spectroscopy

Also, as discussed earlier, an electrocatalytic analyzer has been designed to monitor oxygen concentrations in-situ.

7.2 Terminology

There are a number of terms used to categorize the different types of in-situ monitors, as shown in Figure 7-1.

Cross-stack in-situ monitors measure a pollutant level across the complete diameter or a major portion of the diameter of a stack or duct. Stratification effects are lessened by the use of cross-stack instruments, since an average reading is taken over a relatively long sample path. There are two types of cross-stack monitors: single pass and double pass. Single-pass and double-pass transmissometers have been discussed earlier, and the distinction holds for in-situ gas monitoring systems.

- Single-pass systems locate the light transmitter and the detector on opposite ends of the optical sample path. Since the light beam travels through the flue gas only once, these systems are termed single pass.

- Double-pass systems locate the light transmitter and the detector on one end of the optical sample path. To do this, the light beam must fold back on itself by the use of a retroreflector. The light beam will traverse the sample path twice in going from the instrument housing to the retroreflector and back to the instrument. Double-pass systems are easier to service than single-pass systems, since all of the active components are in one location.

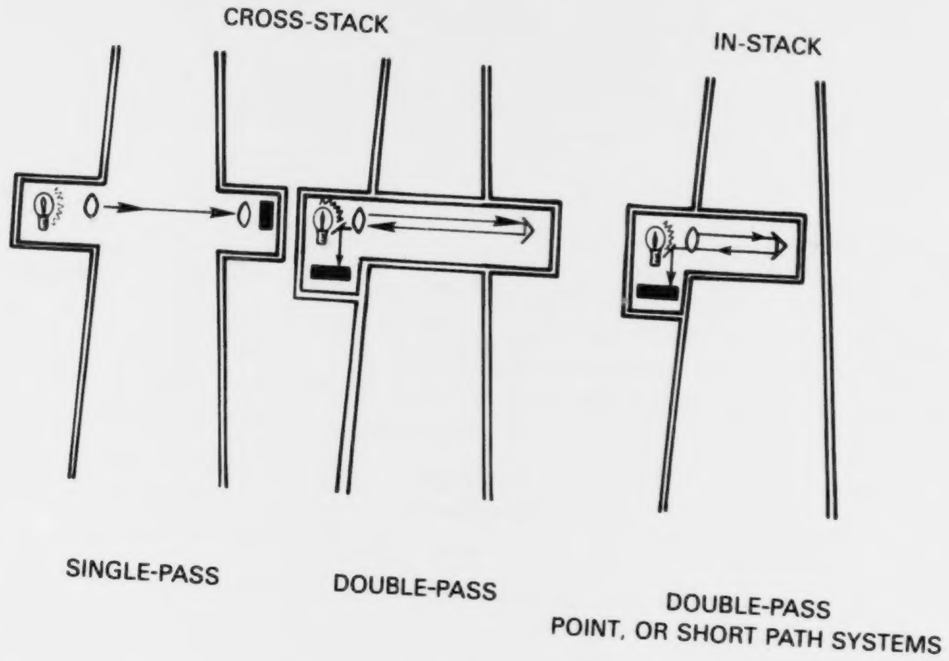

FIGURE 7-1

TYPES OF IN-SITU MONITORS

In-stack, in-situ systems monitor emission levels by using a probe that measures over a limited sample pathlength. All of the commercial optical in-stack monitors are double-pass systems (the in-stack electrocatalytic oxygen monitor discussed earlier is not an optical system). The pathlength may vary from 5 cm to a meter. A retroreflector, usually made of quartz, is located at the end of the probe. The in-stack systems are also termed short-path monitors. The siting of such systems should follow the same guidelines as those given for extractive systems. The location should be chosen carefully so that consistent levels of emissions can be accurately monitored.

There are currently only three vendors of in-situ optical gaseous emission monitors. Environmental Data Corporation (EDC) uses the technique of differential absorption to monitor CO_2, SO_2, and NO and the gas filter correlation technique to monitor CO. Contraves Goerz markets an instrument that measures SO_2, NO, CO_2, and CO levels by the gas-filter correlation method. Lear Siegler, Inc. (LSI), utilizes second derivative spectroscopy to measure SO_2 and NO levels. The following discussion of each of these methods is intended to provide the reader with a background in these new technologies so that informed evaluations may be made of the commercially marketed systems.

7.3 In-Situ Cross-Stack Analyzers

7.3.1 Differential Absorption Spectroscopy

The technique of differential absorption spectroscopy used in the EDC cross-stack gas monitor is similar to that used in the NDUV extractive analyzers discussed in Section 5.2. A diffraction grating is used in this analyzer to obtain a narrow band of radiation over which the pollutant molecule will absorb energy. A grating disperses light from an ultraviolet lamp and light of the appropriate wavelength is detected: one wavelength for monitoring the pollutant level, another to serve as a reference wavelength (Figure 7-2).

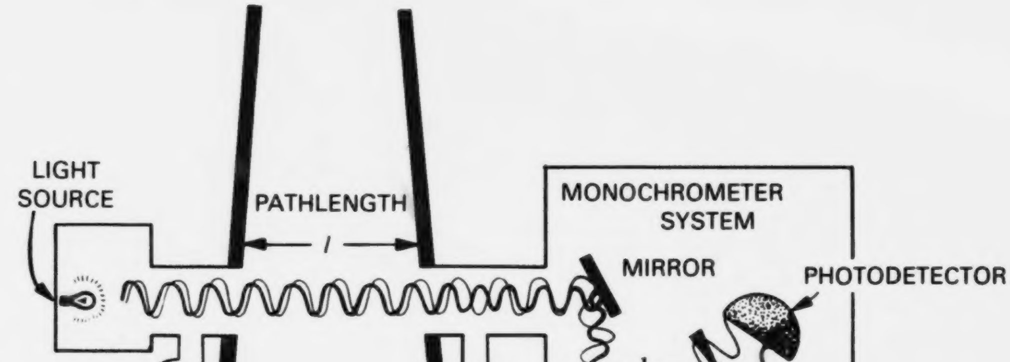
LIGHT SOURCE
PATHLENGTH
l
MONOCHROMETER SYSTEM
MIRROR
PHOTODETECTOR
I_o
CHOPPER
I
BLOWER
STACK
DIFFRACTION GRATING

FIGURE 7-2

OPERATION OF IN-SITU DIFFERENTIAL ABSORPTION ANALYZER

The ratio of the intensities, I/I_o produces a signal that is related to the pollutant concentration:

$$I/I_o = e^{-\alpha c l}$$

where:

I = intensity of light at the measuring wavelength

I_o = intensity of light at the reference wavelength

α = absorption coefficient at wavelength λ

c = concentration

l = measuring pathlength

In the differential absorption technique obtaining a ratio of intensities is important in the case of in-stack monitors. Particulates in the flue gas will attenuate the amount of light energy passing through the optical path. This is the principle of measurement in the opacity monitors. If the light attenuation is the same for the light energy at the measuring wavelength and at the reference wavelength, each intensity would be reduced by a constant factor.

$$I_p = K I_{wp}$$

$$I_{o_p} = K I_{o_{wp}}$$

$$\frac{I_p}{I_{o_p}} = \frac{K I_{wp}}{K I_{o_{wp}}} = \frac{I_{wp}}{I_{o_{wp}}}$$

where:

K = fraction of light attenuated by particulates in the gas stream

I_p = light intensity at measuring wavelength with particulate attenuation

I_{wp} = light intensity at measuring wavelength without particulate attenuation

I_{o_p} = light intensity at reference wavelength with particulate attenuation

$I_{o_{wp}}$ = light intensity at reference wavelength without particulate attenuation

This satisfies the requirement demanded of all in-situ monitors that particulates not interfere in the analytical method. Interference caused by broad-band absorption of water vapor or other molecular species should similarly cancel out if the measuring and reference wavelengths do not differ too greatly.

Optical depth, used in in-situ and remote monitoring, is defined as the concentration of the gas times the optical measuring pathlength. The Beer-Lambert relation for light absorption gives a dependence on the pathlength l. A cross-stack monitor set up to measure pollutants on a stack of a given diameter (d_1) would give different readings if moved to another stack of diameter (d_2) and a correction was not made for the new diameter. To create some type of unit related to the pathlength, the optical depth is defined as the equivalent concentration of the pollutant in a 1-meter path expressed in terms of ppm-meters. A vendor might specify an optical depth range from 0 to 20,000 ppm-meters for a cross-stack instrument. Such an instrument located on a source with a 10-meter stack diameter would have a concentration range from 0 to 20,000/10 = 2,000 ppm. An optical depth is effectively a compression of the real pathlength into a 1-meter length to give an equivalent concentration in ppm-meters. The specification of optical depth values is also important when selecting calibration cells for a cross-stack monitoring system.

The absorption wavelength used for SO_2 monitoring in the EDC analyzer is 309 nm, with a reference wavelength of 310 nm. Nitrogen oxide absorption is detected at a wavelength of 226.5 nm with a reference wavelength of 228 nm. The EDC monitor also detects CO_2 using the differential absorption method, although in this case band-pass filters are employed instead of a diffraction grating. Narrow band-pass filters are chosen to distinguish light at 2 μm for the CO_2 absorption and 2.1 μm for the reference channel. The method for CO_2 is similar to that used in the DuPont extractive analyzer for SO_2 in the ultraviolet, except that in the EDC, infrared radiation is used in the analysis. CO is detected by the gas-filter correlation technique in the EDC system. This method will be discussed later.

The optical systems in cross-stack analyzers are designed to eliminate the effects of particulate matter. Figure 7-3 shows a typical stack-mounted system. The analyzer box contains the major electronics, monochrometer subassembly, and the calibration and zero assemblies as indicated in Figure 7-4. Most of the components are fixed on sliding mounts that can be easily moved in and out of the box for servicing. Figure 7-5 shows the lamp assembly of the EDC system. Figure 7-6 shows the protective housing for the lamp assembly. An EDC analyzer can be purchased to monitor opacity and up to four gases.

Four 2-inch-square light beams pass through the windows of the light source assembly of a typical EDC analyzer. A single ultraviolet beam will pass from the lamp assembly to the analyzer box to detect SO_2 and NO. The IR beam will split in two before passing through the flue to the analyzer box. Separate channels are used to monitor CO_2 and CO. The EDC analyzer is a single-pass system for the measurement of pollutant gases. The opacity channel, however, is a double-pass system, sending a beam of visible light from the analyzer assembly through the fourth 2-inch-square hole of the light source assembly and back again to the analyzer box.

Further information on this system may be obtained from:

Environmental Data Corporation
608 Fig Avenue
Monrovia, California 91019

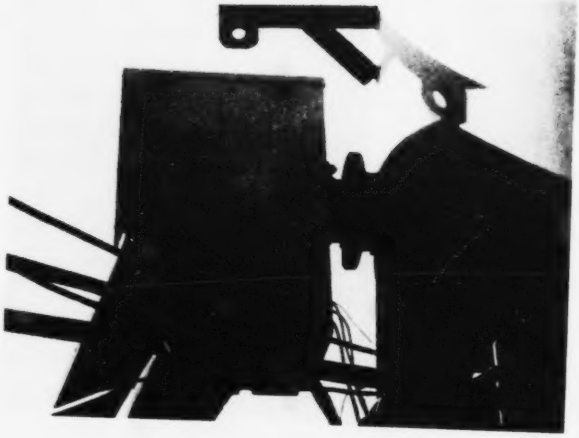

FIGURE 7-3

MOUNTED EDC CROSS-STACK IN-SITU ANALYZER

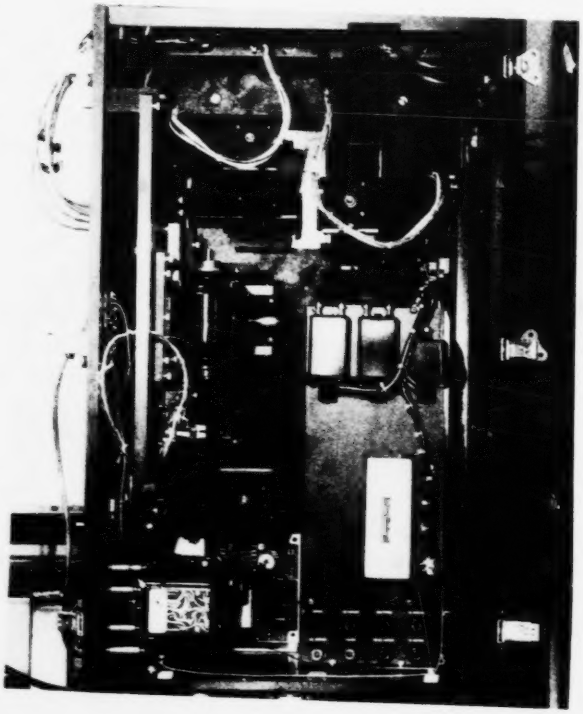

FIGURE 7-4

INTERNAL VIEW OF ANALYTICAL SECTION OF THE EDC ANALYZER

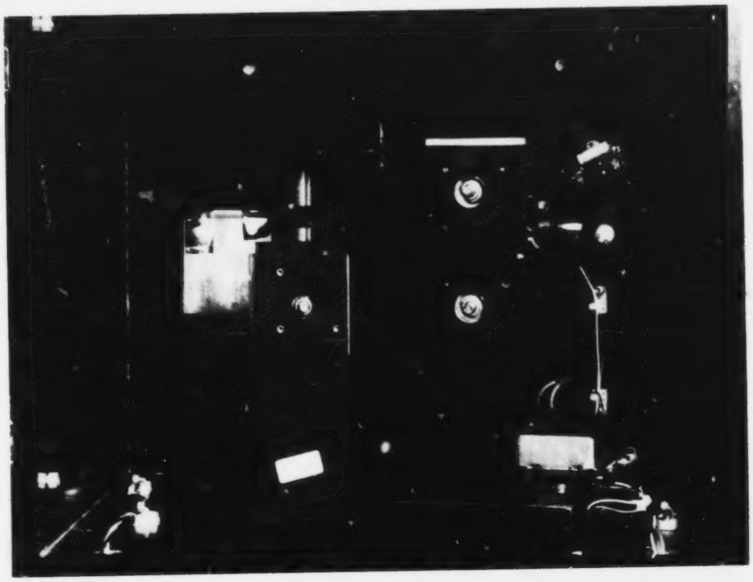

FIGURE 7-5

INTERNAL VIEW OF THE EDC LIGHT SOURCE ASSEMBLY

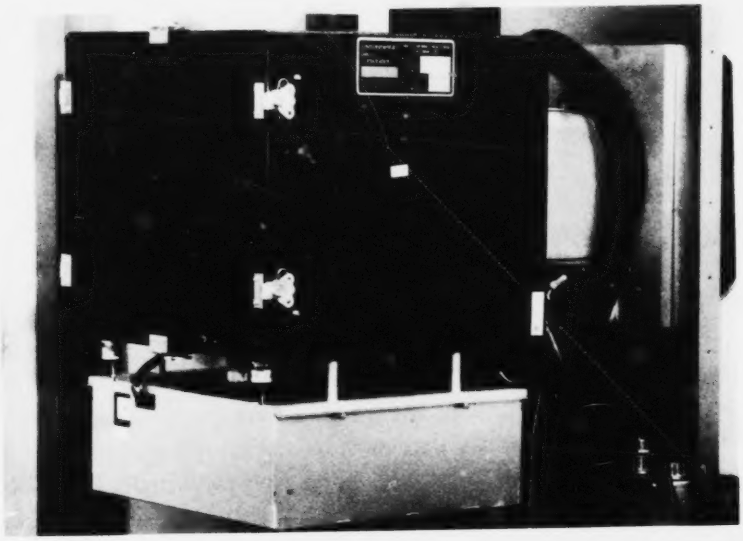

FIGURE 7-6

DIFFERENTIAL ABSORPTION SPECTROMETER INSTALLED AT RESEARCH TRIANGLE PARK SOURCE SIMULATOR FACILITY

7.3.2 Gas-Filter Correlation Spectroscopy

The gas-filter correlation (GFC) method is used in the EDC analyzer to monitor CO and is exclusively used in an analyzer produced by Contraves Goerz Corporation (originally developed and marketed to monitor CO_2, CO, SO_2, and NO). The method shows potential in both in-situ and remote emissions monitoring.

There are a number of optical configurations that can be designed into a GFC system. The essential feature of such a system, however, is the gas-filter cell (Figure 7-7).

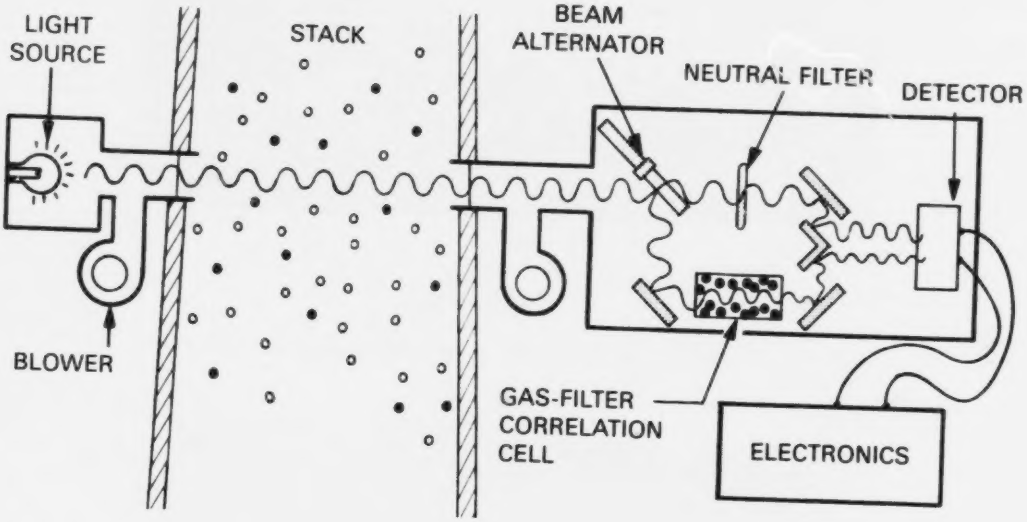

FIGURE 7-7

OPERATION OF A CROSS-STACK GAS-FILTER CORRELATION SPECTROMETER

First, consider a down or zero condition where there is no pollutant gas in the stack. Light, generally in the infrared, is emitted from a lamp and passes through the empty stack to an analyzer where it is split into two separate beams. One beam passes through a neutral filter and the other through the gas-filter correlation cell. This cell contains enough of the gas being analyzed so that most of the energy contained in the individual absorption lines of the gas will be removed. Light of wavelengths not absorbed by the specified gas is not removed and passes on to the detector. This results in a reduction in light energy after the beam traverses the correlation cell.

In most GFC instruments, a neutral density filter is chosen to reduce the amount of light energy in the other beam by an equal amount. The neutral density filter reduces the energy from all of the wavelengths in the beam before it reaches the detector. The gas-filter cell only cuts out energy at the absorption wavelengths. With the proper choice of a neutral density filter and gas concentration in the correlation cell, the amount of energy reaching the detector from each beam is the same, and the system is said to be balanced [Figure 7-8(a)].

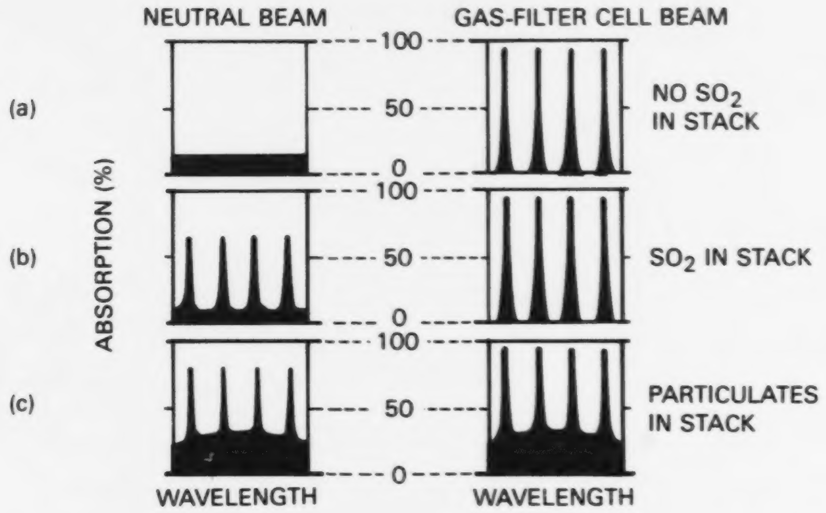

FIGURE 7-8

ABSORPTION PRINCIPLES OF A GAS-FILTER CORRELATION ANALYZER

Next, consider the condition where pollutant gas is in the stack. The beam again traverses the stack, but in this case pollutant molecules are present and absorb light energy at wavelengths corresponding to their absorption spectra. Since the gas-filter correlation cell was chosen to absorb energy at these same wavelengths, the absorption is already complete in the correlation cell beam, and the detector will see the same signal as it did when the stack was clean. The beam passing through the neutral density filter, however, will have less energy than previously, since light was selectively absorbed by the pollutant gas in the stack. The difference in energy between the two beams can be related to the pollutant concentration and is monitored at the detector [see Figure 7-8(b)].

Particulates will reduce the intensity equally in each of the beams. If the two signals are ratioed, the effect of particulate matter will cancel out. Note that particulate interference is equal in both graphs of part (c) of Figure 7-8. Molecules with spectral patterns near that of the pollutant molecule being measured will not affect the measurement if they do not "correlate" or overlap with the pollutant spectral pattern. If there is some overlap, some interference will result.

The GFC method has been found to be a very sensitive and specific method in the infrared. The ability to monitor a large number of absorption lines provides greater sensitivity, in some cases, than can be obtained with the differential absorption technique using only filters. The GFC method is an NDIR method; the light is not dispersed.

The instrument manufactured and marketed by Contraves Goerz uses two detectors instead of one, as shown in Figure 7-9.

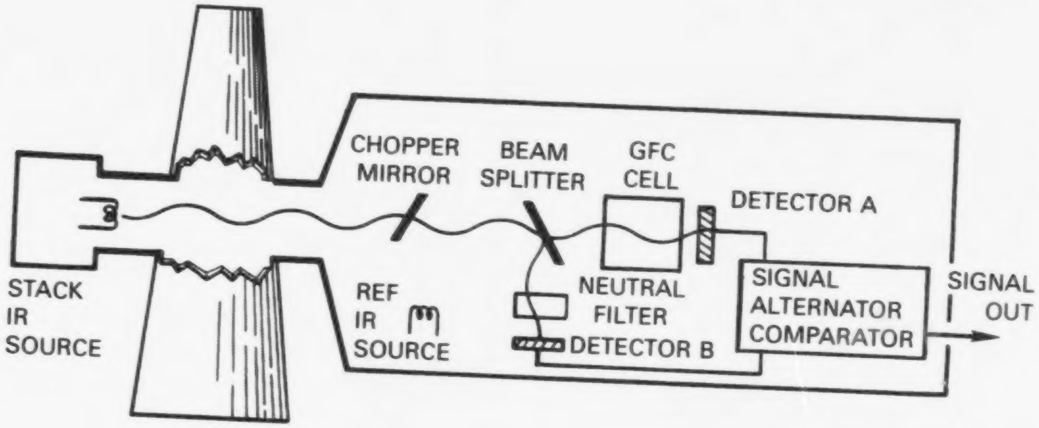

FIGURE 7-9

THE CONTRAVES GOERZ CROSS-STACK GFC MONITOR

A reference IR source is placed in the analyzer portion of this single-pass system to detect concentration levels in a slightly different manner than described previously. When the light from the stack infrared source passes through the flue gas and is divided between the correlation cell and neutral filter, the higher signal coming from the detector after the correlation cell is electrically attenuated. The attenuated signal is adjusted automatically to the same value as the signal given by the other detector after the neutral density filter. A rotating mirror then switches to the light from the IR reference source in the analyzer and blocks out the light coming from across the stack. This time the signal received from each detector will be different. The signals are electronically subtracted to give a signal related to the gas concentration. This two-step procedure is employed to eliminate any effects related to differences in the sensitivity of the two detectors and also to provide a means for a zero and calibration check. The Contraves Goerz system uses only one correlation cell containing all of the four gases, CO, CO_2, SO_2, and NO. Full advantage is taken of the spectral characteristics of these molecules to prevent problems of interference in the measurement.

More information may be obtained on this system from:

Contraves Goerz Corporation
610 Epsilon Drive
Pittsburgh, PA 15238

7.3.3 Advantages and Limitations

The currently marketed cross-stack gas analyzers in principle present many advantages over extractive monitoring systems. A cross-stack system may allow greater flexibility in site selection, since an average sample reading is taken over a relatively long path. It should be noted, however, that gas stratification in a duct or stack is a two-dimensional phenomenon, not one-dimensional. A cross-stack monitor can linearly average concentrations over its measuring path, but does not properly weigh the contributions of stratified areas to the measurement. For severe cases of stratification, the problem of obtaining representative concentration values may be comparable to the problems encountered by point monitors. Quartz or glass cells, used in cross-stack optical systems for calibration, reduce the time and expense that result with span gas cylinders and the associated plumbing of extractive systems. The calibration cells need only be certified by the manufacturer and are not required to be checked periodically, as are span gas cylinders.

One of the principal marketing features of cross-stack analyzers is that a single instrument can monitor a number of gases and even opacity. The cost of such a monitor can be comparable to the purchase price of three or four separate instruments combined in an extractive system. The operating costs of in-situ monitors can be less than those of extractive systems, since zero and span gases are not required for the 24-hour checks. There are also fewer separate components in an in-situ system, so problems with chillers, heat-traced lines, valves, and pumps are avoided.

The Code of Regulations gives an alternative method that a single-pass, cross-stack monitor can use to perform a system zero check. Three or more calibration cells are inserted into the system operating in the measuring cross-stack mode. The upscale readings given by these known cells then can be extrapolated to a zero value. A graph showing this extrapolation is reported by the source operator. The zero drift values for 2 and 24 hours must be within 2 percent of span before the instrument can be accepted by EPA. A problem has arisen in some cases that it is difficult to distinguish zeroing and upscale calibration checks by this method.

There are, however, a number of disadvantages associated with the cross-stack monitors. An in-situ cross-stack monitor can monitor only one flue or stack at a time. Costs might be prohibitive if a number of stacks must be monitored. In such a case, multiple probes and sampling lines leading into a single extractive system might be the better choice. Problems with optical misalignment, vibration affecting the optical systems, and failure of electronic components also can occur. It is common among vendors of these instruments to offer service packages where the systems are periodically checked by a company serviceman. A service package generally will ensure that a system will continue to function, but the cost involved may bring the operating expenses to a level comparable to that of an extractive system.

7.4 In-Situ, In-stack Analyzers: Second-Derivative Spectroscopy

At the present time, only one instrument is manufactured that monitors SO_2 and NO in-stack. This is the Lear Siegler (LSI) second-derivative, stack-gas monitor. Although the second-derivative technique is somewhat more complicated than those discussed earlier, an understanding of the method is necessary if a source operator or agency observer has to make an evaluation of different monitoring systems.

The LSI in-situ monitor is shown in detail in Figure 7-10, and in a typical source application, mounted to a stack wall, in Figure 7-11.

This monitor analyzes the gas in-situ; the gas is not extracted, but is monitored as it exists in the flue gas stream. The tip of the probe contains the measuring chamber, which senses across a distance of 10 cm. The instrument therefore does not measure cross-stack. It is an in-stack point monitor or short-path monitor. Care should be taken when siting such a system, since a representative location is required to be monitored by the EPA. The guidelines given for siting of the probe of an extractive system could be followed in choosing the location of an in-stack monitor, although EPA has not published any specific siting criteria for this technique outside of the general criteria for representative measuring.

The probe of this system consists of a ceramic thimble surrounding the measuring chamber. The thimble and a metal V bar in front of the thimble prevent particulates from entering the chamber. The filtering action of the thimble prevents particulate matter from fouling the optical surface of the retroreflector shown in Figure 7-12. Gas diffuses into the measuring cavity and the pollutant can be monitored. Ultraviolet light is sent from the analyzer section, down the length of the probe, through the measuring cavity, to the retroreflector. A quartz corner cube reflector is used in this case, and the light is bounced back to the analyzer section. The pollutant gas only occupies the small measuring cavity and not the entire length of the probe assembly.

The technique of second-derivative spectroscopy (SDS) utilizes the spectral absorption features of a molecule in a manner somewhat different from the methods discussed for the cross-stack monitors. A diffraction grating selects the specific absorption wavelengths, but instead of just sitting on a specific wavelength as is done in differential absorption techniques, a scanner or moving slit scans back and forth across the central wavelength.

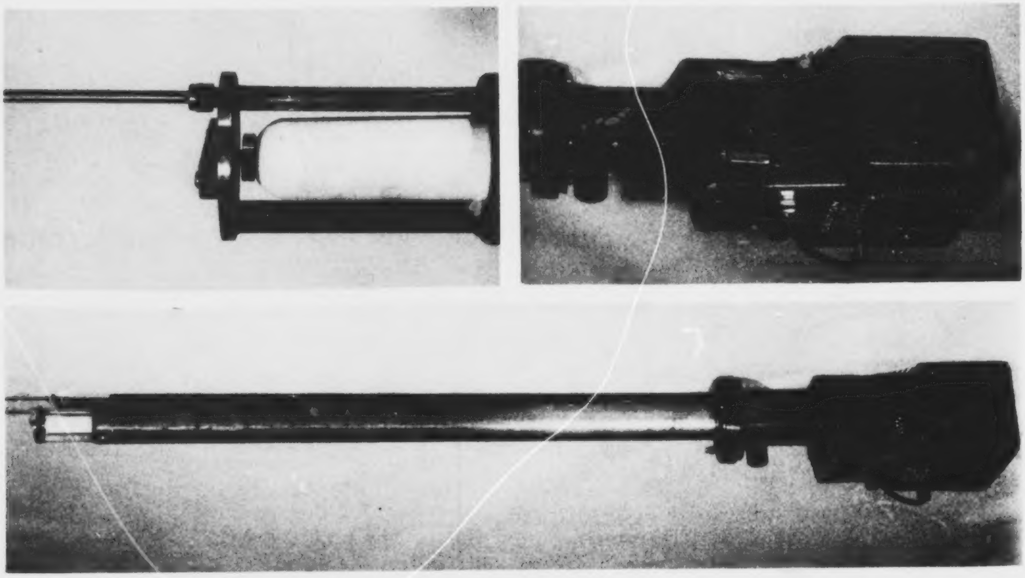

FIGURE 7-10

THE LEAR SIEGLER IN-STACK IN-SITU SO_2-NO ANALYZER

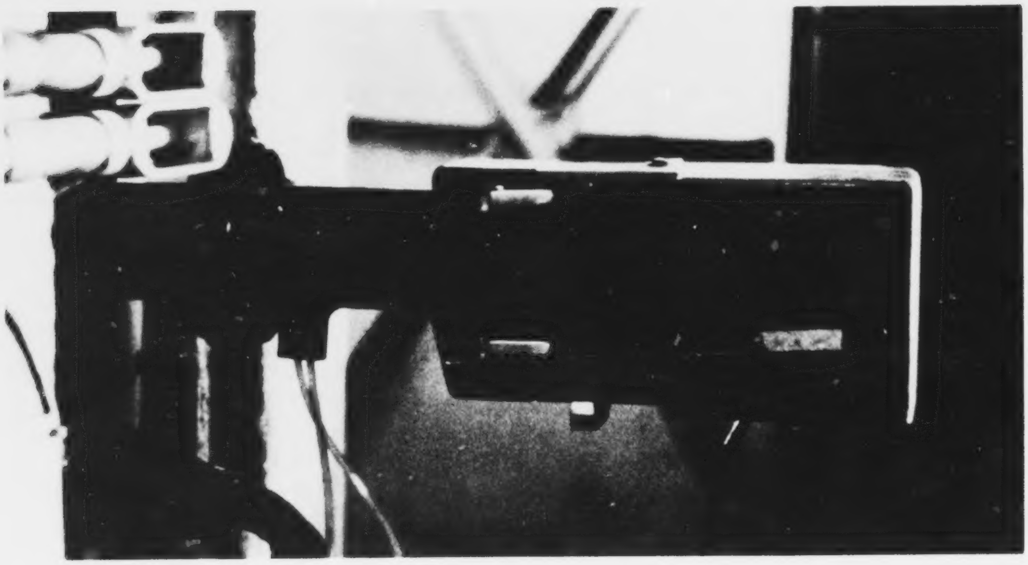

FIGURE 7-11

SECOND-DERIVATIVE SPECTROMETER INSTALLED AND OPERATING
AT A STEAM GENERATING FACILITY

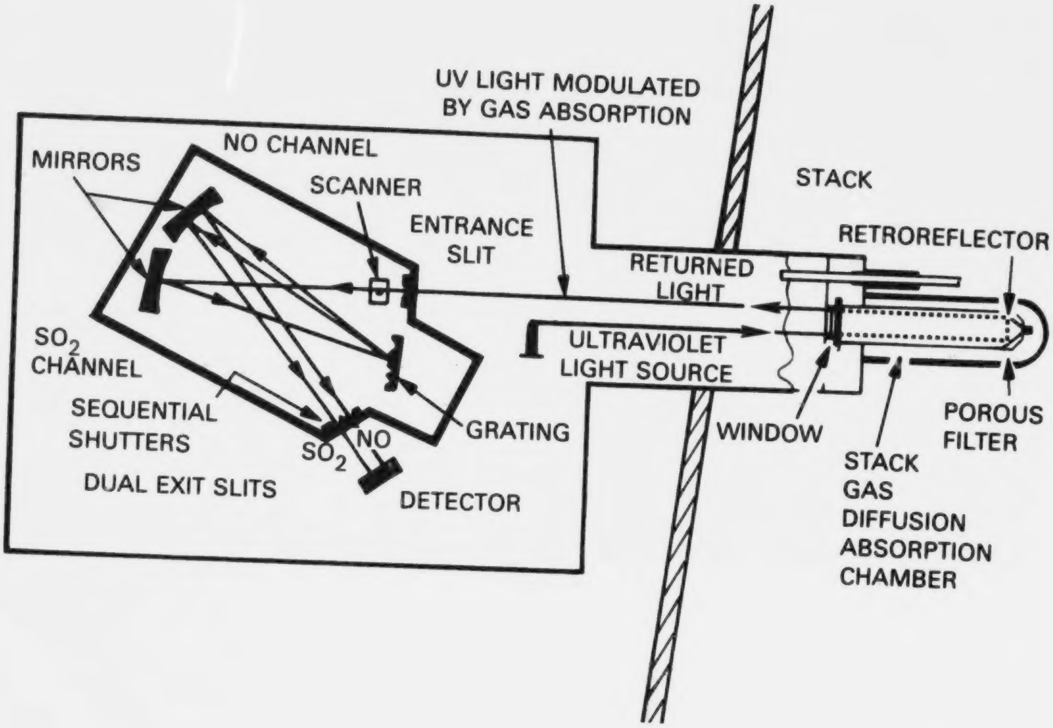
UV LIGHT MODULATED BY GAS ABSORPTION
NO CHANNEL
MIRRORS
SCANNER
ENTRANCE SLIT
STACK
RETROREFLECTOR
RETURNED LIGHT
ULTRAVIOLET LIGHT SOURCE
SO_2 CHANNEL
SEQUENTIAL SHUTTERS
SO_2
NO
GRATING
WINDOW
POROUS FILTER
DUAL EXIT SLITS
DETECTOR
STACK GAS DIFFUSION ABSORPTION CHAMBER

FIGURE 7-12

OPERATION OF THE SECOND DERIVATIVE IN-STACK MONITOR

In this instrument, light at 218.5 nm, corresponding to the maximum of an SO_2 absorption peak in the ultraviolet, is utilized. The scanner modulates the light at wavelengths from 217.8 to 219.2 nm, across the width of the absorption peak (Figure 7-13).

The results of this scanning are seen at the detector of the instrument. Before looking at the signal that such a scan of the absorption peak would produce on a detector, consider the detector signal produced by a scan of a broad band absorption (Figure 7-13). Here, there is no strong absorption peak, but a gradual decrease in transmission (increased absorption) as the light varies from the lowest scanned wavelength to the highest scanned wavelength.

The moving mask scans over the wavelengths of light separated by the diffraction grating and then goes back over the same wavelengths. One cycle, back and forth, will take 0.09 second (a period of 0.09 = 11 cycles per second). The resultant signal seen at the detector will be in the form of a sine wave or an alternating current, with a period t = 0.09 second and frequency of 11 cps.

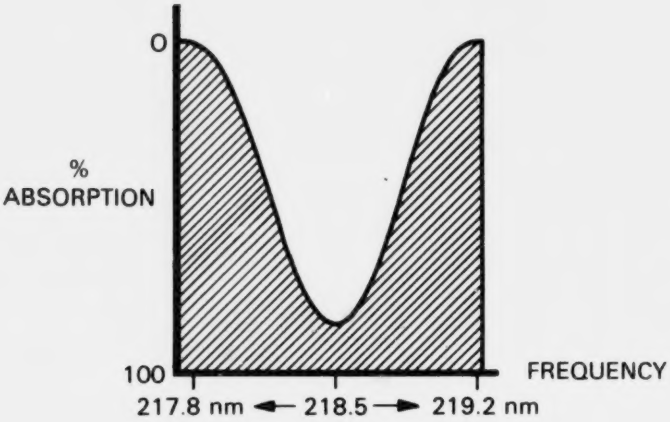

FIGURE 7-13

ULTRAVIOLET LIGHT WAVELENGTHS
SCANNED BY SPECTROMETER MOVING MASK

In the following case there is no broad band absorption, but instead, a sharp absorption peak caused by the presence of an SO_2 molecule (Figure 7-14). Following the same argument, where the slit moves back and forth in a time period of 0.045 second there is an extra hump in the detector signal (Figure 7-15). Although the mask scans the wavelengths at a frequency of 11 cycles per second, maxima will appear at the detector signal at double the frequency, or 22 cycles per second. Since the amplitude of the peaks seen at the detector are related to the amount of light absorption, the amplitude is related to the amount of pollutant gas in the optical path.

Electronically, the concentration of a pollutant is determined by tuning in on the frequency which is double that of the frequency of movement of the scanner, much like tuning a radio. A radio station produces a signal at a given frequency and a dial is adjusted to receive that station. A station with a strong transmitter will produce a louder signal than a weaker station. In the second-derivative method, the instrument is tuned to a frequency of 2f, where f is the scanning frequency of the mask. A strong signal from the detector indicates strong absorption and a high concentration of SO_2. A weak signal at this frequency indicates a lower concentration of SO_2.

This discussion has so far dealt with the mechanical aspects of the detection method. The question arises, however, what does this have to do with second derivatives? Taking a derivative of a function is equivalent to determining the slope. For example, for a broad-band absorption curve similar to that of Figure 7-16(a), the first derivative gives a constant negative value and the second derivative gives a value of zero, since the slope of Figure 7-16(b) is zero.

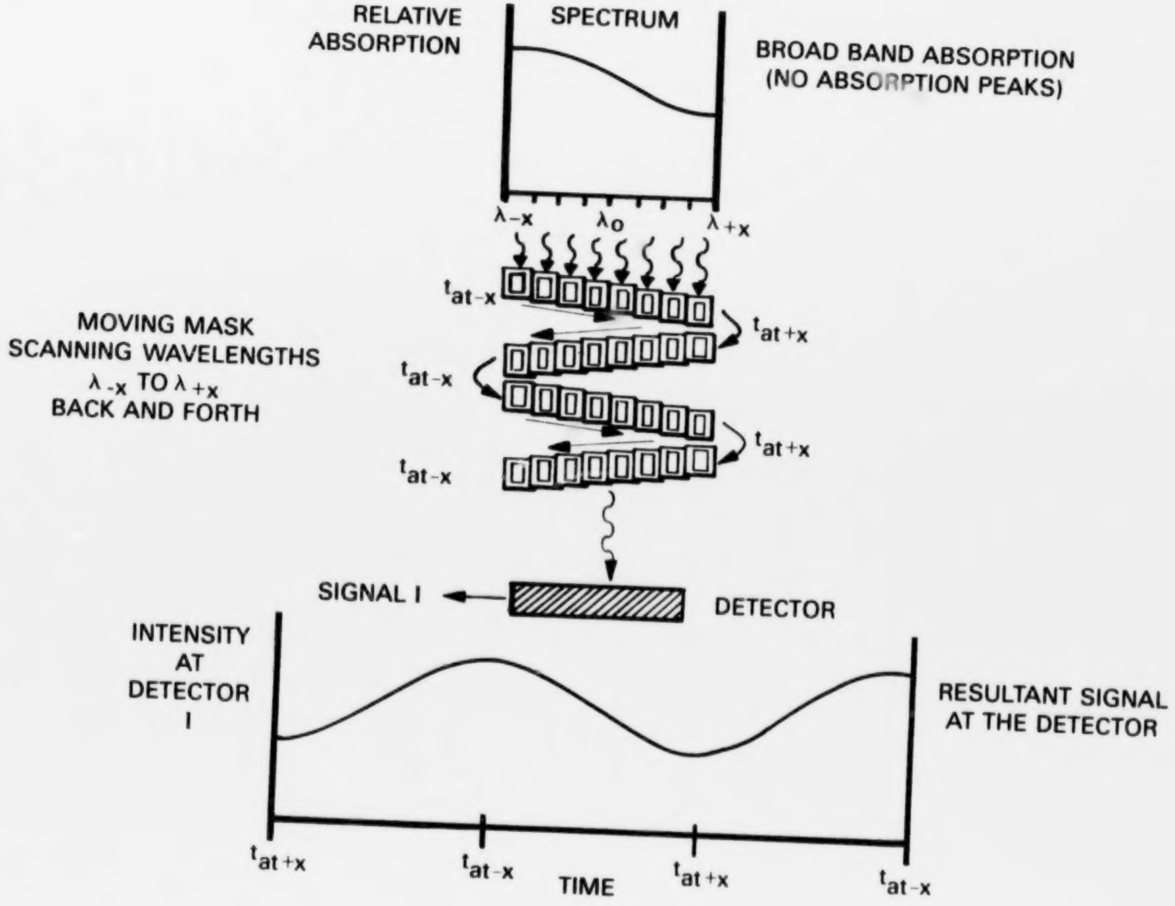
RELATIVE ABSORPTION
SPECTRUM
BROAD BAND ABSORPTION (NO ABSORPTION PEAKS)
λ_{-x}
λ_o
λ_{+x}
t_{at-x}
t_{at+x}
MOVING MASK SCANNING WAVELENGTHS λ_{-x} TO λ_{+x} BACK AND FORTH
t_{at-x}
t_{at+x}
t_{at-x}
SIGNAL I
DETECTOR
INTENSITY AT DETECTOR I
RESULTANT SIGNAL AT THE DETECTOR
t_{at+x}
t_{at-x}
TIME
t_{at+x}
t_{at-x}

FIGURE 7-14

SCANNING A BROAD BAND ABSORPTION

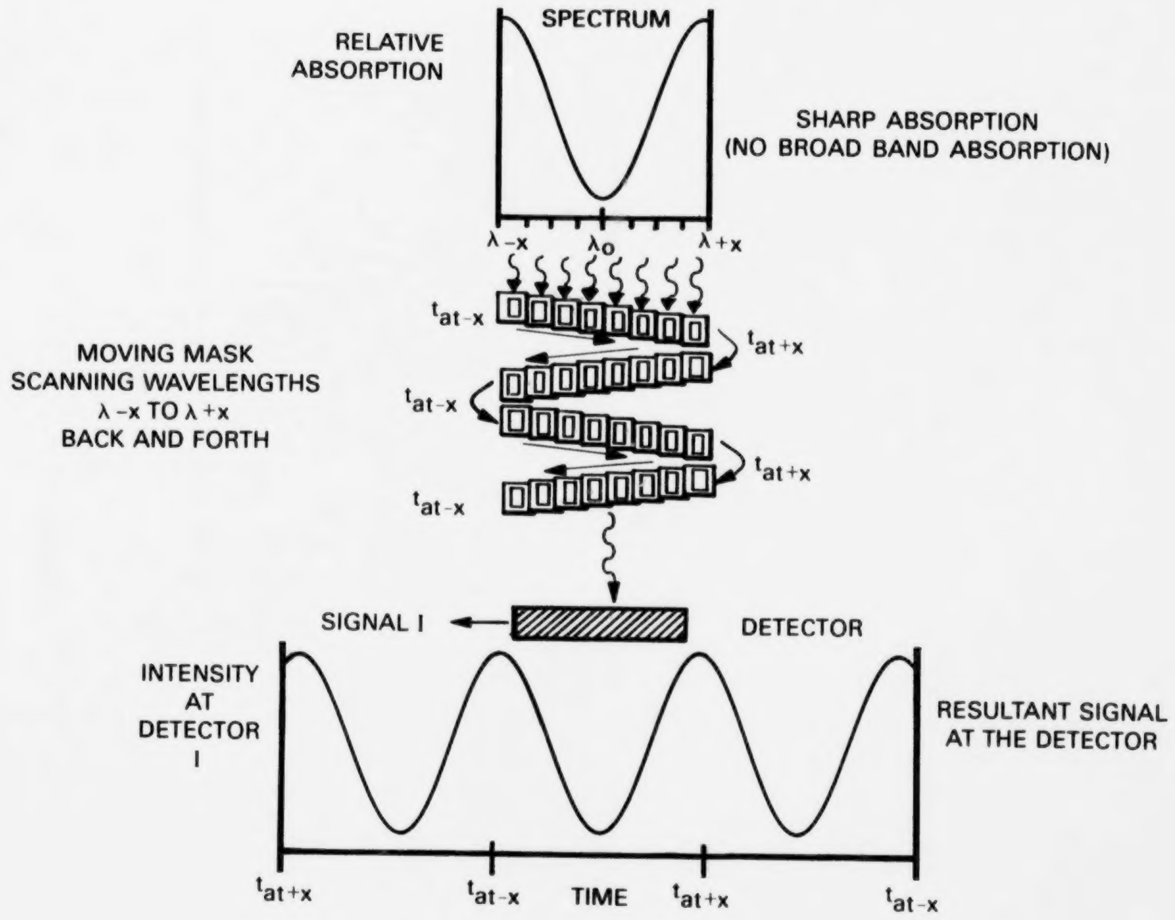
RELATIVE ABSORPTION
SPECTRUM
SHARP ABSORPTION (NO BROAD BAND ABSORPTION)
λ -x
λo
λ +x
t at-x
t at+x
MOVING MASK SCANNING WAVELENGTHS λ -x TO λ +x BACK AND FORTH
t at-x
t at+x
t at-x
SIGNAL I
DETECTOR
INTENSITY AT DETECTOR I
RESULTANT SIGNAL AT THE DETECTOR
t at+x
t at-x
TIME
t at+x
t at-x

FIGURE 7-15

SCANNING AN ABSORPTION PEAK

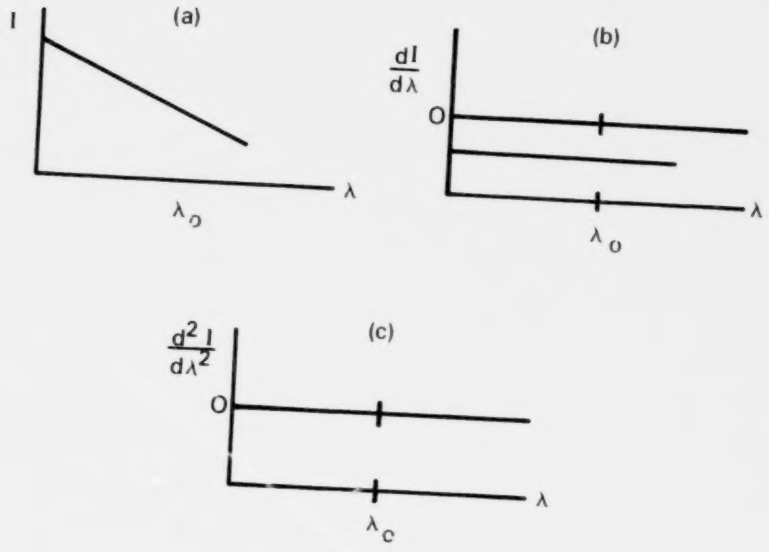

FIGURE 7-16

FIRST AND SECOND DERIVATIVES OF LINEAR ABSORPTION

For an absorption peak, the curvature and, therefore, the slope change, depending upon the wavelength. The first derivative, evaluated at a given wavelength, will reflect the curvature of the absorption peak [Figure 7-17(a)]. The second derivative indicates the curvature of the first-derivative curve [Figure 7-17(b)]. Since the slope of b changes often, the second-derivative curve is much more complicated, as shown in Figure 7-18.

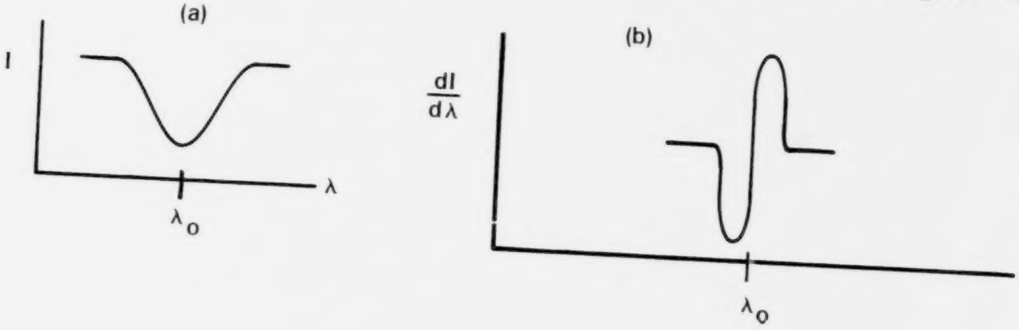

FIGURE 7-17

FIRST DERIVATIVE OF AN ABSORPTION CURVE

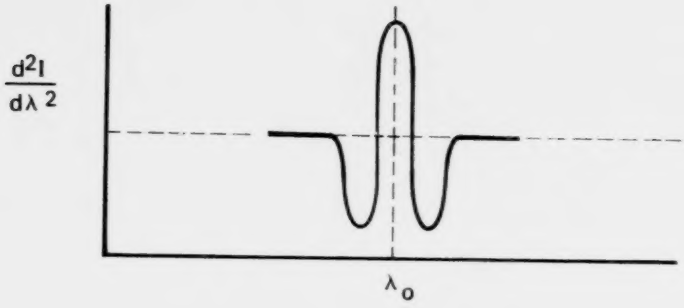

FIGURE 7-18

SECOND DERIVATIVE OF AN ABSORPTION CURVE

In the mechanical method used in second-derivative spectroscopy, the actual detector output appears much like that shown in Figure 7-15. The amplitude of the detector signal at the frequency of 2f is proportional to $d^2I/d\lambda^2$ evaluated at λ_o. The second-derivative source monitoring instruments constructed by LSI do not produce curves like that of Figure 7-18. They only produce the value of $d^2I/d\lambda^2$ evaluated at λ_o. The signal at the detector is given by

$$S = \frac{\delta^2}{4}\frac{d^2I}{d\lambda^2}$$

where δ equals the distance from λ_{-x} to λ_{+x} (in the example this would be 1.8 nm). By an expansion of Beer-Lambert's law

$$\frac{d^2I}{d\lambda^2} = -cl\frac{d^2\alpha}{d\lambda^2}I$$

where:

α = absorption coefficient

c = concentration

l = optical pathlength of gas of interest

The resultant expression for the signal is

$$S = -c\frac{l\delta^2}{4}\frac{d^2\alpha}{d\lambda^2}I$$

or

$$\frac{S}{I} = Kcl$$

where K is constant.

This is the actual instrument output that is proportional to both gas concentration and optical pathlength.

By dividing S by I, problems caused by variations in the source intensity, optical misalignment, and broad-band absorption from other gases or particulates are avoided. This results because a change in I by a constant factor will induce an identical change in S. Determining the ratio of the two cancels out the effect.

The second-derivative in-stack monitor is of course limited to monitoring one stack at a time. Vibration also can be a problem, since extreme cases can affect the optical system. One of the most common problems in this and similar electro-optical systems is the failure of electronic components. The complicated circuitry of such systems in some cases may lead to a higher probability of component failure. A significant feature of the LSI system is that zero and span gases can be used to flood the sample chamber to a pressure greater than the stack static pressure. This provides an alternate method to the use of calibration cells if desired. The calibration cells may be used for daily span checks and would save the expense of span gas and the associated plumbing systems. The LSI second-derivative source monitor also may be modified to measure ammonia concentrations. More information may be obtained on the analyzer from:

Lear Siegler, Inc.
Environmental Technology Division
74 Inverness Drive East
Englewood, CO 80110

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CHAPTER 8

MEASURING, RECORDING, AND REPORTING REQUIREMENTS

8.1 Introduction

The development of a continuous emissions monitoring system extends beyond the choice of a set of opacity and gas analyzers. The analyzers, themselves, must measure emissions within specified time periods. The measurements, however, then must be recorded in some manner. After the data are recorded, they must be converted into units of the emissions standard, such as lbs/10^6 Btu.

Calculated emission values that are in excess of the standard must then be reported on a quarterly basis to the EPA Administrator. In addition, the EPA regulations of 40 CFR 60.7 require the reporting of the following:

- Time and magnitude of excess emissions
- Nature and/or cause of excess emissions
- Corrective and/or preventative action taken to prevent their recurrence
- Zero/span calibration values
- Normal measurement data
- Log of inoperative periods
- Repair and maintenance logs
- Performance, test, calibration data

A complete emissions monitoring system, therefore, requires some means of recording the analyzer data. Strip-chart recorders have been used most often, but data loggers and computer systems are beginning to become popular. Data processors have been developed specifically to reduce the time necessary to evaluate and report excess emissions. A summary of the process of measuring-recording-reporting is given in Figure 8-1.

A data reporting system may encompass anything from the manual reduction of raw strip chart data and compilation of associated data to the near fully automatic preparation of complete excess emission reports, including most of the mentioned data requirements. The choice of the data reduction and reporting system may be the most important factor in the overall emission monitoring system, since it greatly affects the amount of manual effort involved in meeting the NSPS requirements.

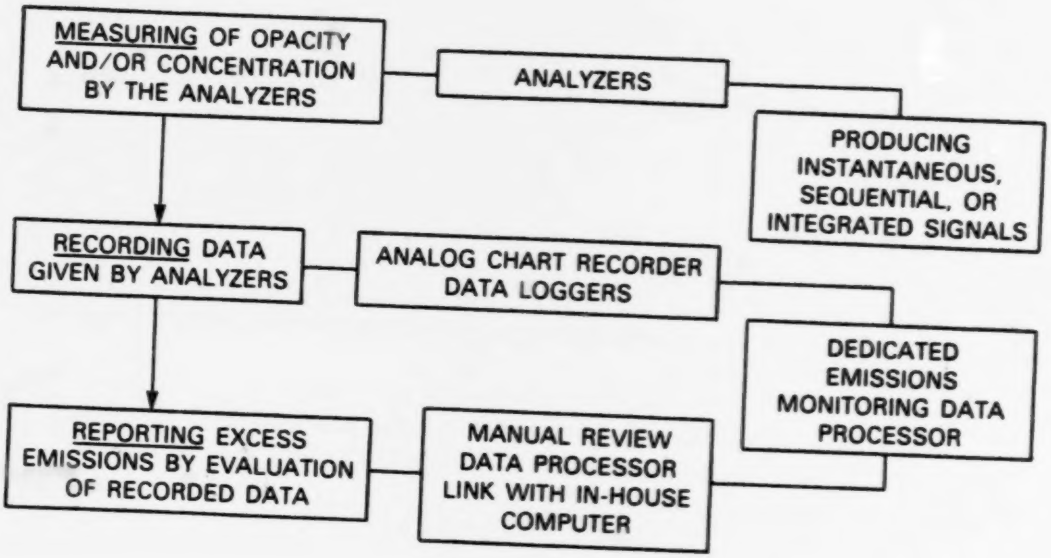

MEASURING OF OPACITY AND/OR CONCENTRATION BY THE ANALYZERS
ANALYZERS
PRODUCING INSTANTANEOUS, SEQUENTIAL, OR INTEGRATED SIGNALS
RECORDING DATA GIVEN BY ANALYZERS
ANALOG CHART RECORDER DATA LOGGERS
DEDICATED EMISSIONS MONITORING DATA PROCESSOR
REPORTING EXCESS EMISSIONS BY EVALUATION OF RECORDED DATA
MANUAL REVIEW DATA PROCESSOR LINK WITH IN-HOUSE COMPUTER

FIGURE 8-1

POSSIBLE METHODS OF MEASURING-RECORDING-REPORTING

This chapter will review some of the techniques and problems involved in completing an emissions monitoring system. A discussion is given in Appendix C on the F-factor method used by the EPA in converting concentration data into the units (lb/10^6 Btu) required by the New Source Performance Standards.

8.2 Measuring Requirements

The measuring requirements for continuous emissions monitors are important, since they can influence the choice of the recording system. The requirements for systems applied to new sources (NSPS) are given in Table 8-1.

TABLE 8-1

MEASURING REQUIREMENTS

Opacity – Monitors	Completion of one cycle of operation (sampling and analysis) every 10 seconds
SO_2, NO_x, – CO_2, O_2	Completion of one cycle of operation (sampling and analysis) every 15 minutes

The data generated by the monitoring instrument give much more information than is actually required. The measuring periods given in Table 8-2, for gases, allow for the use of sequential analyzers or systems designed to sample from more than one stack or duct. The DuPont UV 463 analyzer is an example of a sequential system, since it operates on 5-minute cycles to convert NO to the measured NO_2. Monitoring systems that come under the State plans (existing sources) may have measuring requirements different from those given above.

The actual data that can be used to satisfy these measuring requirements may be of three types:

- Instantaneous values taken at the end of each time period
- Values obtained by integrating data over each time period
- Values obtained by averaging a number of data points over each time period

The method used often will be determined by the type of gas and opacity analyzers purchased and by the recording method. The measuring requirements are tied in with the recording requirements. A consideration of both often will dictate the choice of the complete monitoring system.

8.3 Recording Requirements and Systems

8.3.1 Requirements

All of the data that an emissions monitor may produce do not need to be recorded. The NSPS requirements for recorded emissions data are given in Table 8-2.

TABLE 8-2

RECORDING REQUIREMENTS

Opacity –	An average of a minimum of 24 equally spaced data points taken over a 6-minute period is to be recorded every 6 minutes.
SO_2, NO_x, – CO_2, O_2	An average of a minimum of 4 equally spaced data points taken over an hour is to be recorded every hour.

Since a monitor may produce a continuous trace on a strip chart for a 6-minute or 1-hour period, a larger amount of data may be obtained than is actually used. The regulation, however, specifies only the minimum number of points that need to be averaged and recorded. It is often easier to design systems that integrate the continuous data over the averaging periods. These would be acceptable under the regulations.

The recording requirements were established to coincide roughly with the type of data obtained from the manual EPA reference methods. Since it was hoped to correlate in-stack opacity data with the visible emissions data obtained by an observer using EPA Method 9, the same averaging and recording requirements were given. It should be noted that by dividing 24 into 6 minutes (360 seconds), the recording requirements give a 15-second measuring time. Opacity monitors are, however, required to complete one cycle of measurement every 10 seconds as discussed in Section 9.2. This inconsistency is not particularly important, since an average of 36 data points would serve just as well to satisfy the regulation. Integrating systems for the analyzer generally are available as an option for some opacity monitors.

EPA Method 6 for SO_2 specifies a 20-minute sampling time (for fossil-fuel-fired steam generators). EPA Method 7 for NO_x specifies 4 grab samples to be taken at 15-minute intervals. The continuous monitoring regulation for SO_2 and NO_x analyzers of an average of 4 data points taken over each 1-hour period corresponds roughly with these reference methods.

The recording requirements for monitoring systems on existing sources covered by a State plan may be somewhat different than those given in Part 60 of the Code of Federal Regulations. The State averaging periods are chosen to correspond to the averaging period specified by the State compliance test method. Further information should be obtained from the State if the compliance test methods differ from the Federal methods.

8.3.2 Recording Systems – Continuous Analog Recording

There are a variety of methods used to record data from analytical devices. The strip-chart recorder is encountered most frequently in continuous source monitoring applications. However, the availability of low-cost digital recording devices provides alternatives for the recording and processing of emissions data.

A continuous analog record is obtained by using some type of chart recorder. The voltage or current signal from the source analyzer is fed into the recorder and a driving mechanism produces a trace of the signal strength as a function of time. The types of analog recorders most often encountered in engineering applications are either circular-chart or strip-chart recorders.

The circular-chart recorder, although used extensively in process control applications has some disadvantages in recording emissions data. First, the chart length for a single chart is limited. For instance, the length of a trace at 50 percent of full scale on a 12-inch diameter chart would be only 21 inches. A 20 percent opacity trace would give an even smaller effective chart length and would require frequent changing of the chart paper. Second, the curved lines of the circular-chart paper make it difficult to compare and interpret data. Time resolution becomes poorer at smaller values of the measured parameter. On the other hand, circular-chart recorders present all of the data at a glance for a given time period. They have been developed to be used in many types of field situations and may be obtained at relatively low cost.

Strip-chart recorders provide greater versatility in monitoring applications. There are over 100 companies marketing some form of strip-chart recorder in the United States today. This method dominates the recording field for several reasons:

- It is the only feasible way of making long-term, easy-to-read records of high-speed phenomena.
- It is highly efficient in its ability to pack information into available space.
- Proper arrangements make it easy to analyze multiple-trace data.
- On a per-square-foot basis, the paper is almost always much less costly than that for circular charts.

There are a number of factors that should be considered when evaluating a recorder for a given systems application. An evaluation should consider:

- Type of unit – Portable, rack-mountable, or table model
- Type of signal input (volts, millivolts, amps) accepted and range
- Type of pen (capillary, felt tip, heated stylus, electrically charged stylus)
- Type of paper take-up (take-up roll, folded paper)
- Appropriate chart speed
- Accuracy as percent of full scale
- Response time consistent with EPA emissions monitoring requirements
- Chart supply provisions – At the required chart speed, number of days' supply of chart paper that can be stored in the unit
- Maintainability – Features that may enhance the serviceability and reliability of the instrument

Since the recorder is a part of the continuous monitoring system, the response time, drift, and accuracy requirements established in the EPA performance specifications must be considered when choosing the recorder itself. If a recorder is chosen that has poor response time and limitations in recording accuracy, the overall monitoring system will suffer. There are many factors that contribute to the relative inaccuracy (relative to the EPA reference method) of a monitoring system. The recording system does not need to be one of these factors if a proper choice of the system is made initially.

8.3.3 Recording Systems – Intermittent Digital Recording

The analog chart recorders give a continuous record of the signal produced by an analyzer. The digital recorder or data logger, however, selects some value (either an instantaneous or integrated value) after a given time period and records it. For this reason, a digital system may be characterized as recording data over intermittent periods. These periods may be short, a tenth or hundredth of a second or less; but for too short a period, the printed data produced might be unmanageable.

It should be noted that a data logger is not a computer or a microprocessor. A computer can process data, convert it into emission rates, and record it in specified formats. Data loggers merely record data at specified intervals. There are two options available on digital recorders that extend their utility. These are an alarm monitoring capability and the ability to print out by exception. A data logger, therefore, could be set to send off an alarm or print out data once a specified value is reached. It could not, however, compute the emission rate by the F-factor method and print it. A microprocessor or computing system would be necessary in this case.

There are several advantages to digital instruments (1):

- They produce a permanent printed output record that can be readily understood without having to interpret tracings, as in the case of a chart recorder.
- They can be modified to provide values that can be read directly (ppm, percent).
- Data can be read quickly with less chance of misinterpretation.
- Since the data have already been converted into digital form, the data logger can be interfaced easily with a computer.
- The data may be duplicated easily, without the problems of shrinking or distortion that may occur with a strip-chart record.

There are a few significant disadvantages with digital recording systems, such as the following:

- They are more complex and more difficult to troubleshoot than an analog recorder.

- It is more difficult to detect trends from data given by a digital recorder.
- It is more difficult to compare digital data, either between different instruments or over different time periods.
- It is difficult to troubleshoot intermittent or peculiar causes of failure, since the data are averaged and an instantaneous signature of the system is not available as with a strip-chart recorder.

The difficulty of detecting trends has been overcome in some systems by recording the digital data on cassette tape. The tape can be read off on a computer and the data for the time period of interest then can be graphed automatically with a plotter. This method provides a convenient means of storing the continuous monitoring record. Cassette tapes are easily handled and cataloged and detailed graphs need only be reproduced when desired.

8.3.4 Recording Systems – Data Processors

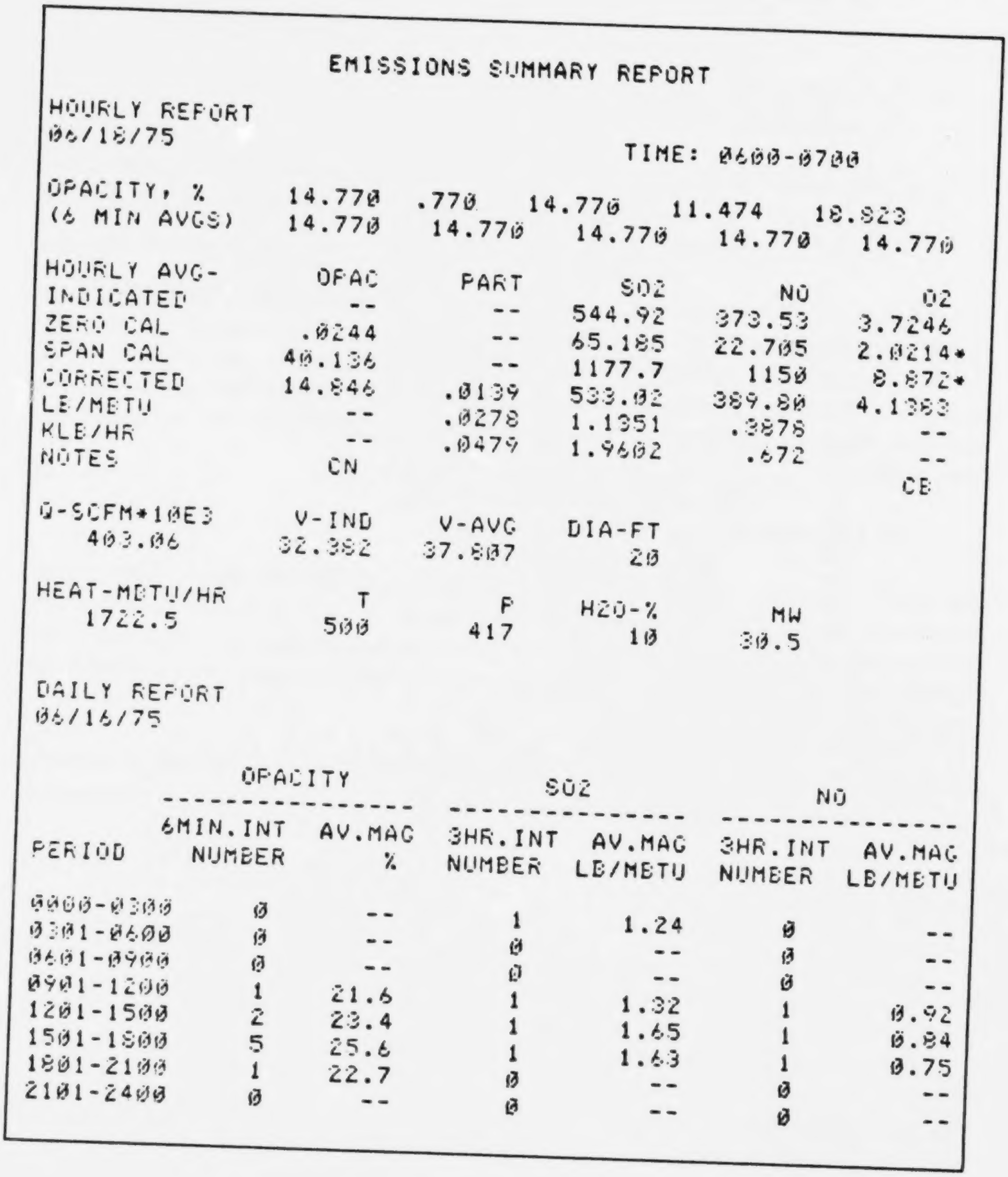
The most convenient method of handling continuous monitoring data is with a data processor. Several firms involved in the manufacture of stack monitors have seen the need for the instrumentation that will rapidly average and compute data in terms of the emission standard. An example of the type of data that can be produced by a computerized system is given in Figure 8-2.

Formats of course can vary, but it is important to eliminate the manual task of reducing the data. The preparation of the required EPA quarterly reports then becomes much easier.

There are two data processing methods that generally are used in continuous monitoring systems. These are:

- Analyzer – Analog-to-digital (A/D) – Large general purpose computer or data processing system
- Analyzer – Dedicated continuous monitor data acquisition system

The first method utilizes the plant computer or data processing system. The analog signals from the flue gas monitors first must be converted into digital form by use of a data logger or an A/D converter; however, the data processing system may already have this feature as a part of its software. The digital signals then are sent to the computer, which is programmed to accept them and perform the necessary calculations for the resultant printout. There are several problems with this method. First, the plant computer, designed or purchased for process applications, may not have enough storage or programming facility to accommodate the continuous-monitoring requirements. Second, when the computer is down, the continuous-monitoring data may be lost or difficult to retrieve. The in-house



```
                       EMISSIONS SUMMARY REPORT
HOURLY REPORT
06/18/75
                                                  TIME: 0600-0700

OPACITY, %        14.770   .770    14.770    11.474    18.823
(6 MIN AVGS)      14.770    14.770    14.770    14.770    14.770

HOURLY AVG-          OPAC       PART        SO2         NO         O2
INDICATED              --         --     544.92     373.53     3.7246
ZERO CAL            .0244         --     65.185     22.705    2.0214*
SPAN CAL           40.136         --     1177.7       1150     8.872*
CORRECTED          14.846      .0139     533.02     389.80     4.1383
LB/MBTU                --      .0278     1.1351      .3878         --
KLB/HR                 --      .0479     1.9602       .672         --
NOTES                  CN                                          CB

Q-SCFM*10E3         V-IND      V-AVG     DIA-FT
   403.06          32.382     37.807         20

HEAT-MBTU/HR            T          P      H2O-%         MW
   1722.5             500        417         10       30.5

DAILY REPORT
06/16/75

                   OPACITY                  SO2                   NO
          -----------------      ----------------      ----------------
          6MIN.INT   AV.MAG      3HR.INT   AV.MAG      3HR.INT   AV.MAG
PERIOD     NUMBER        %       NUMBER   LB/MBTU      NUMBER   LB/MBTU

0000-0300     0         --          1       1.24          0         --
0301-0600     0         --          0         --          0         --
0601-0900     0         --          0         --          0         --
0901-1200     1       21.6          1       1.32          0         --
1201-1500     2       23.4          1       1.65          1       0.92
1501-1800     5       25.6          1       1.63          1       0.84
1801-2100     1       22.7          0         --          1       0.75
2101-2400     0         --          0         --          0         --
                                                          0         --
```

FIGURE 8-2

DATA FROM TYPICAL DATA PROCESSOR DESIGNED FOR CONTINUOUS SOURCE MONITORING APPLICATIONS computer capability and existing utilization will have a direct bearing on any decision to extend its use to continuous-emissions-monitoring applications.

The second method involves making a major purchase for a system that will be dedicated to processing only the continuous monitoring data. A number of systems are available on the market that are designed to do this. These systems can average automatically opacity and gaseous emissions data, can compute emissions by the F-factor method using the input of the pollutant gas and diluent gas monitor, and can provide a summary report of the data on an hourly, weekly, or monthly basis. The systems can generate an alarm signal and also may record the data on magnetic tape. The Emissions Summary Report shown in Figure 8-2 is an example of the type of output that can be produced.

The dedicated systems may save time and money in the long run. Many source operators will first purchase the gas analyzers and rely on strip-chart output for the data-recording requirements. If the monitoring system is working properly and the data are reliable, consideration is given to a data processor in order to reduce the amount of time spent analyzing what can amount to volumes of data. Many operators have found it convenient to keep the chart recorders to provide an easily interpreted record of the trends occurring during the source operation. Cross checks then can be made between the two systems; if either malfunctions, the data may not be lost.

8.4 Reporting Requirements

Continuous-emissions-monitoring data, obtained for the purpose of satisfying the EPA regulations, must be reported on a quarterly basis. The originally proposed regulations, which appear in the Federal Register, September 11, 1974, required that all of the data were to be reported to the EPA office. This proposal received a large number of comments from both agency and industry personnel. It was generally felt that the amount of data would be excessive and that the expense and manpower involved would be unjustified. Changes were subsequently made in the promulgated October 6, 1975, regulations, effectively requiring the reporting of only excess emissions.

Excess emissions are defined in the Subpart of the Code of Federal Regulations dealing with the affected industry. In Subpart D 40 CFR 60, for example, excess emissions are defined for fossil-fuel-fired steam generators. Under 40 CFR 60.45g:

- Opacity. Excess emissions are defined as any 6-minute period during which the average opacity of emissions exceeds 20 percent, except that one 6-minute average per hour of up to 27 percent opacity need not be reported.

- Sulfur dioxide. Excess emissions for affected facilities are defined as any 3-hour period during which the average emissions (arithmetic average of three contiguous 1-hour period) of sulfur dioxide as measured by a continuous monitoring system exceed the applicable standard under § 60.43.

- Nitrogen oxides. Excess emissions for affected facilities using a continuous monitoring system for measuring nitrogen oxides are defined as any 3-hour period during which the average emissions (arithmetic average of three contiguous 1-hour periods) exceed the applicable standards under § 60.44.

Excess emissions may be defined differently for sources other than fossil-fuel-fired steam generators. Reference should be made to the appropriate subparts of the Code of Federal Regulations for the promulgated emission standards and average times (e.g., Subpart J for petroleum refineries, see Table 2-2 for a reference listing of the CFR subparts).

Since a majority of the sources affected by the continuous-monitoring requirement will be coal- and oil-fired power plants, a few additional comments on the excess emissions defined in Subpart D are appropriate.

- The definition of excess emissions for opacity appeared December 5, 1977, in 42 FR 61537. Note that an exception of one 6-minute period at a level of 27 percent opacity is allowed. Prior to this promulgation, 2 minutes of soot blowing at 40 percent opacity were allowed. This soot blowing allowance was retained, but expressed in terms of the 6-minute average, i.e.,

$$27\% \text{ allowable opacity} = \frac{2 \times 40\% + 4 \times 20\%}{6}$$

- Standards for SO_2 and NO_x emissions from fossil-fueled steam generators are expressed in lbs/10^6 heat input. The emissions are to be calculated by using the F-factor method. The F-factor method essentially reduces the amount of data necessary to compute the emissions rate. A thorough explanation of the method is given in Appendix C.

- Only excess emissions are required to be reported. All of the data produced by a continuous source analyzer need not be converted into units of the standard. Only the data reported as being in excess of the standard has to be expressed in these terms. However, there should be some means to single out excess emissions from the unreduced data. A source with varying emission and excess air rates may have to convert all of the data into units of the standard. See the preamble on page 46250 of the October 6, 1975, Federal Register for further clarification.

Reports of excess emissions determined from a continuous monitoring system are to be reported on a quarterly basis. Each period of excess emissions also requires an explanation of the reasons for the high values. These may be identified as startups, shutdowns, or malfunctions of the affected facility. Also, if there were no periods of excess emissions during the reporting quarter, a report to that effect must be made.

The problem of monitoring equipment malfunctions is a matter of serious concern to the continuous monitoring program. It is obvious that an improperly operating continuous monitor serves neither the source operator nor the control agency. In order to keep aware of the instrumental problems that inevitably develop, occasions of instrument downtime, repair, or significant readjustment also must be documented and explained in the quarterly report. Many agencies are now developing inspection programs for these systems in an effort to insure that reliable emissions data can be obtained.

The source operator also must maintain a file of all of the continuous monitoring data, including records of the Performance Specification Test, adjustments, repairs, and calibration checks. The file must be retained for at least 2 years and is required to be maintained in such a condition that it can be easily inspected by a field enforcement officer.

The details of the reporting requirements are given in 40 CFR 60.7. Although no specific format for the quarterly reports is required, the EPA Office in Region 8 has developed a form for their use that includes the points required by the Code of Federal Regulations (Figure 8-3). Although other formats may be suitable, this format could serve as a guide for these reports.

QUARTERLY EXCESS EMISSIONS REPORT (EER)
For
Fossil Fuel-Fired Steam Generators, Subpart D
Suggested Format for Sources in Region VIII*
Minimum Requirements Under Section 60.7 (see instructions)

Part 1. This report includes all the required information under section 60.7 for:

a. Quarterly emission reporting period ending: (circle one)

Mar. 31 June 30 Sept. 30 Dec. 31

b. Reporting year: ______________

c. Reporting date: ______________

d. Person completing report: ______________

e. Station name: ______________

f. Plant location: ______________

g. Person responsible for review and integrity of report:

h. Mailing address for person in 1-g above:

i. Phone number for 1-g, above:

Part 2. Instrument Information, complete for each instrument

a. Monitor type (circle one): Opacity SO_2 NO_x O_2 CO_2

b. Manufacturer: ______________

c. Model no.: ______________

d. Serial no.: ______________

e. Installation date: ______________

Part 3. Excess emissions (by pollutant)

Use Table I: Do not complete for diluent monitors; attach separate narrative per instructions.

FIGURE 8-3

SUGGESTED FORMAT FOR QUARTERLY EXCESS EMISSIONS REPORT

Part 4. Conversion factors (not for diluent monitor report)

a. Diluent measured (O_2 or CO_2) ______________

b. F-Factor value used ______________

i. Published or developed ______________

ii. F, Fc, or Fw ______________

c. Basis for gas measurement data (wet or dry)

d. Zero and Cal values used, by instrument:

	Opacity (%)	SO_2 (ppm)	NO_x (ppm)	Diluent (% or ppm - circle one)
Zero				
Cal				

Part 5. Continuous Monitoring System operation failures

See Table II: Complete one sheet for each monitor, including diluent: attach separate narrative per instructions.

Part 6. Certification of report integrity, by person in 1-g, above:

THIS IS TO CERTIFY THAT TO THE BEST OF MY KNOWLEDGE, THE INFORMATION PROVIDED IN THE ABOVE REPORT IS COMPLETE AND ACCURATE.

NAME ______________

SIGNATURE ______________

TITLE ______________

DATE ______________

*Suggested Format for Subpart D sources in: Colorado, Montana, North Dakota, South Dakota, Utah, Wyoming

FIGURE 8-3

SUGGESTED FORMAT FOR QUARTERLY EXCESS EMISSIONS REPORT—Continued

TABLE Ia - Excess Emissions Summary by Week[1]

OPACITY: Week[6] ________ Day[7] ________ Limit ________

Excess Emission Range Category	Percent of Emission Limit	Number of 6-Minute Periods During Day[2]	Reason Codes[3]
A	100-125		
B	126-150		
C	151-175		
D	176-225		
E	> 225		

SO_2 Week[6] ________ Limit ________

Excess Emission Range Category	Percent of Emission Limit	Number of 3-Hour Periods During Week[2]	Reason Codes[3]
A	101-108		
B	109-120		
C	121-135		
D	136-155		
E	> 155		

NO_x Week[6] ________ Limit ________

Excess Emission Range Category	Percent of Emission Limit	Number of 3-Hour Periods During Week[2]	Reason Codes[3]
A	101-108		
B	109-120		
C	121-135		
D	136-155		
E	> 155		

[1] Format to be used in automatic data-handling systems; Table I (2) to be used in manually-prepared reports to show each excess emission.

[2] As defined in 60.45(g).

[3] List in descending order the three most frequent codes, by number, followed in parenthesis by the number of occurrences of the reason.

[6] Begin Sunday morning at midnight; list date of the Sunday starting the week.

[7] List the day of the week; e.g., Tuesday.

FIGURE 8-3

SUGGESTED FORMAT FOR QUARTERLY EXCESS EMISSIONS REPORT—Continued

TABLE I

Excess Emissions (by pollutant)

Date	Time From - To	Pollutant	(% O_2 or CO_2)	Magnitude* Lb./10^6 BTU

*as defined in the instructions from the applicable section of the Federal Register; attach narrative of causes, etc.

TABLE II

Continuous Monitoring System Operation Failures

Date	Time* From - To	Instrument	Effect on Instrument Output

*attach narrative of causes, etc.

FIGURE 8-3

SUGGESTED FORMAT FOR QUARTERLY EXCESS EMISSIONS REPORT—Continued

8.5 References

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2. Floyd, J. R., "The Implementation of the NSPS Continuous Emission Monitoring Regulations in EPA, Region VIII," Paper 78-35.1, presented at the 71st Annual Meeting of the Air Pollution Control Association, Houston, Texas, June 25-30, 1978.

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CHAPTER 9

EQUIPMENT SELECTION

9.1 Introduction

The selection of source monitoring instrumentation often has been a problem for those needing to comply with air pollution regulations. Fortunately, instrumentation developed over the past several years is workable and reliable.

One of the major problems in the past with continuous monitoring systems was not with the monitor itself but with the system. Practically all of the instruments marketed performed within specifications in the laboratory, but when set up in an extractive system or placed across a stack, many problems would arise. These problems still occur, but with the experience that has been gained, most of the problems now can be solved. Although source monitors sold today are more carefully constructed and have better specifications than their predecessors, the same limiting performance factors relate to system and the application. For this reason, lists of instruments and their specifications, which periodically appear in air pollution magazines (and in this handbook), should be used only as a guide in selecting a monitor.

In this chapter, selection guides are given for both opacity and gas monitors (Tables 9-1 and 9-2). These guides are intended to answer a number of questions when evaluating a monitor. No single instrument could meet all of the criteria implied by these questions. The purchaser of the equipment should evaluate which features are important or unimportant for the particular application.

The lists of vendors in this chapter (Tables 9-3 through 9-8) were compiled from the trade literature, responses from information requests, and personal communications with vendors at instrument shows. It is felt that these lists and tables represent the state of the market as of March 1979. There are many other companies that manufacture gas analyzers. However, many of these are not designed for measurements at source level concentrations or source conditions. Only those companies whose instruments are designed specifically for source applications and who are seriously competing in this market are listed here. The competitive nature of this market leads to frequent changes in product lines and the occasional demise or reorganization of a firm. Ideally, these tables should be updated on a 6-month basis to remain current. In any case, the tables should be viewed only as guidelines to the market.

TABLE 9-1

OPACITY MONITORS – SELECTION PROCEDURES

Choice of Instrument Method

Determine the Type of System Required

- Single Pass
- Double Pass
- Multi-Parameter (opacity & gases)
- Stack Diameter & Optics Requirements – Operational Distance
- Cross-stack Permanent
- In-stack Portable
- Breech Pipe System
- Automatic Features

Choice of the Specific Instrument

EPA Requirements

1. Does it meet EPA requirements for the following:

Peak Spectral Response	500–600 nm
Mean Spectral Response	500–600 nm
Angle of View	≤5°
Angle of Projection	≤5°

2. Does it or will it satisfy EPA performance requirements in terms given in 40 CFR 60 Appendix B?

Calibration Error	≤3% opacity
Zero Drift (24 hr.)	≤2% opacity
Calibration Drift (24 hr.)	≤2% opacity
Response Time	10 sec. maximum
Operational Period	168 hrs.

3. Has the instrument ever undergone a Performance Specification Test?

TABLE 9-1

OPACITY MONITORS – SELECTION PROCEDURES–Continued

4. Is it necessary that the monitor meet the Performance Specifications for the given application?
5. What experience can the vendor demonstrate under the relevant EPA requirements and in other applications?

Design Characteristics

---

1. Cost
2. Blower System
    - a. Is it required? (is the stack pressure positive or negative? how does pressure vary during startup and shutdown?)
    - b. Air flow rate capacity ($ft.^3/min.$)
    - c. Filters – type, number of stages, filter capacity?
    - d. Shutters – for system or power failure?
    - e. Design of instrument purge system (i.e., is air supplied by blower actually effective in keeping optics clean)?
3. Optical Assembly
    - a. Sensitivity to ambient light (chopper-modulator)?
    - b. Collimation method (self-correcting?)
    - c. Calibration System
        1. Is same lamp and detector used in zero check?
        2. Is same lamp and detector used in span check?
        3. Is automatic zero calibration correction available?
    - d. Does it have alignment viewing port or sight glass for aligning system?
    - e. Will the assembly adapt to the stack diameter?
    - f. Maintenance Indicators – does the system monitor its operating condition and alert operator to required maintenance?

TABLE 9-1

OPACITY MONITORS – SELECTION PROCEDURES–Continued

4. Electronic System
    a. Analog or digital display?
    b. Easy to wire and set up?
    c. Warning system available? Remote, visible, audible? Alarm set-point?
    d. Automatic zero and calibration checks?
    e. Remote manual calibration available?
    f. Automatic counter-timer for recording excess emissions?
    g. Linear response, units and measurement ranges?
    h. Automatic stack exit correlation available?
    i. Automatic optical density display?
    j. Output requirements (mA or mV)?
    k. Computer interface?
    l. Quick disconnect cables or hard wired?
    m. Recorder module available? Separate recorder required?
    n. Sensitivity to line voltage fluctuations?
    o. What options are available to enhance applications flexibility?

Environmental Requirements

1. Can it operate in a corrosive environment?
2. Will the readings remain stable under varying ambient temperatures?
3. Is the instrument constructed ruggedly enough for the proposed location?
4. Is an explosion-proof cabinet available?
5. Does the instrument satisfy space and weight requirements?
6. Does the instrument severly restrict or modify the flue gas flow?
7. Can the system operate under positive or negative static pressure?
8. Can the instrument withstand vibration if located on or near the stack?

TABLE 9-1

OPACITY MONITORS – SELECTION PROCEDURES–Continued

9. Can the instrumental parts in or near the stack withstand high temperatures and stack temperature fluctuations?
10. Can the optical system of the transmissometer account for alignment changes brought about by changes in stack or duct temperature?

Maintenance and Operational Considerations

1. What type of warranty is available?
2. Is there a guaranteed maintenance-free period? Or guaranteed operational period?
3. Is field installation supervision available?
4. Is user training available?
5. Will the instrument manufacturer assist in the performance specification tests?
6. Are leasing or service contracts available?
7. Are service contracts required?
8. Is a special operator or special maintenance required?
9. Is cleaning or the replacement of parts required on a regular basis? If so – cost and labor? How available are parts?
    a. What are the sizes (costs) of the basic replacement modules?
    b. What test points, diagnostics, decal information, troubleshooting procedures are provided to simplify diagnosis and repair?
    c. Do schematics reference commonly available component descriptions or only factory part numbers?
    d. How complete is technical manual provided with the equipment?
    e. Where are most of the electronics and repairs likely to be encountered – on stack or in the control room?
10. Is the instrument easy to service? Is access to previous service records available?
11. What is the lamp life expectancy? (>20,000 hrs.?)
12. How often do lenses or filters need cleaning or replacement? How easy is this to do?

TABLE 9-1

OPACITY MONITORS – SELECTION PROCEDURES–Continued

13. Would the instrument's location be accessible for servicing?

14. What adjustments or manual checks are required during operation?

15. Is this a new model instrument? When was the last design change?

16. Vendor Characteristics:

    a. What is the vendor's commitment to this product line?

    b. What is the probability that the vendor will be able to service the equipment over its full design life?

    c. What research and development capability does the vendor have in this product line?

    d. What is the availability of applications assistance?

    e. How many service people are actually trained on this product line and where are they located?

    f. What is the company's ability to guarantee compliance with EPA requirements?

TABLE 9-2

GASEOUS MONITORS – SELECTION PROCEDURES

Choice of Monitoring System Extractive or In-Situ

Determine the Type of System Required

1. Is the system needed to monitor a single stack or multiple stacks?
2. How many pollutants are required to be monitored?
3. Can a single monitor be used or are several instruments needed?
4. How severe is gas stratification? Cyclonic flow?
5. What response time is required?
6. How representative will the sample be? (Will conditioning affect the sample?)
7. What are the location requirements for an extractive or in-situ system?

Choice of Physical-Chemical Method of Analysis

First: Determine the following:

1. Type of operation and details of the process.
2. Stack gas composition.
3. Pollutant concentrations and variation.
4. Stack gas temperature and ambient temperature (variations of both).
5. Stack gas velocity and volumetric flowrate.
6. Stack static pressure.
7. Moisture content and dew point of stack gas.
8. Particulate loading.
9. Stack dimensions and possible locations for the monitoring system.
10. Abrasion and corrosion problems.

TABLE 9-2

GASEOUS MONITORS – SELECTION PROCEDURES–Continued

Ask the following questions:

1. Is the method sensitive to interferences at levels characteristic of the source?
   a. H_2O vapor, CO_2.
   b. Entrained mist or condensed vapors.
   c. Heavy particulate loading.
2. Will variable temperature be a problem?
3. Will high and/or varying stack gas velocity and pressure be a problem?
4. Will high temperatures be a problem?
5. Will the method be accurate under conditions experienced at the source?
6. Can the method be adapted to the siting requirements?
7. Will it require so much conditioning of stack gas that accuracy or validity will be questioned?

Choice of the Specific Instrument

EPA Requirements

1. Does it or will it satisfy EPA performance requirements in terms of

	SO_2 & NO_x	O_2 or CO_2
Accuracy	⩽20%	–
Calibration error	⩽5%	–
Zero drift (2 hr. & 24 hr.)	2% of span	⩽0.4% & ⩽0.5%
Calibration drift (2 hr. & 24 hr.)	2.5% of span	⩽0.4% & ⩽0.5%
Response time	15 min. (max)	10 min. (max)
Operational period	168 hrs.	168 hrs.

TABLE 9-2

GASEOUS MONITORS – SELECTION PROCEDURES–Continued

2. Has the instrument ever undergone a performance specification test?
3. How extensive has previous use been? Documentation?
4. Is the response linear over the operating range?
5. What is the signal-to-noise ratio?
6. Would the system be reliable for long term continuous operation?

Design Characteristics

1. Cost? Immediate and long term.
2. Is the design and operation simple?
3. Does it have multi-gas measuring capability?
4. Does it read in the correct range – is auto-ranging capability available?
5. Is the calibration method simple and convenient? Are adjustments simple and convenient? How can the operator verify calibration of the system as it is installed?
6. Does it read out directly in concentration? Does it correct for dilution of air?
7. Can the instrument be easily installed with few alterations to the existing facility?
8. What are the sampling volume requirements? (Will it rob gas from other monitors in an extractive system?) (Will it take too much span gas each time it is calibrated?)
9. What are the power requirements?
10. Does it require compressed air or an air blower?
11. Is the instrument sensitive to power fluctuations?
12. What is the warm-up time after shut-off?
13. Does it have a display analog or digital?
14. Does it have automatic zero and calibration?
15. Is there a warning device? Remote, visible, audible?
16. Is the recorder output compatible with your recorder on data handling system? Is an interface needed?
17. Does the instrument have good accessibility for repairs and service?

TABLE 9-2

GASEOUS MONITORS – SELECTION PROCEDURES–Continued

18. What automatic features are available to alert operator of operating condition or the need for maintenance?
19. What options are available to enhance the flexibility of application of the instrument?

Environmental Requirements

1. Can it operate in a corrosive environment?
2. Will the readings remain stable under varying ambient temperatures?
3. Is the instrument constructed ruggedly enough for the proposed location?
4. Is an explosion-proof cabinet available?
5. Does the instrument satisfy space and weight requirements?
6. Does the instrument severely restrict or modify the flue gas flow?
7. Can the system operate under positive or negative static pressure?
8. Can the instrument withstand vibration if located on or near the stack?
9. Can the instrumental parts in or near the stack withstand high temperatures? And stack temperature fluctuations?

Maintenance and Operational Considerations

1. What type of warranty is available?
2. Is there a guaranteed maintenance-free period?
3. Is field installation supervision available?
4. Is user training available?
5. Will the instrument manufacturer assist in the performance specification test? What is the company's ability to guarantee compliance with EPA requirements?
6. Are leasing or service contracts available?
7. Are service contracts required?
8. Is a special operator or special maintenance required?

TABLE 9-2

GASEOUS MONITORS – SELECTION PROCEDURES–Continued

9. Is cleaning or the replacement of parts required on a regular basis? If so – cost and labor? How available are parts?
10. How often do lenses and/or filters need cleaning or replacement?
11. Is the instrument easy to service? Is access to previous service records available? How many service people are actually trained on this product line and where are they located?
12. Would the instrument's location be accessible for servicing?
13. What adjustments or manual checks are required during operation?
14. Is this a new model instrument or has it been a basic design used for a long time? Are you going to be stuck with a "one of a kind" instrument?
15. When was the last model change?
16. What is the vendor's commitment to this product line?
17. Are wiring diagrams supplied from the manufacturer? If so, are they for your model and accurate? How complete is the technical manual provided with the equipment?
18. Is the instrument safe? Does it use hydrogen? Are the reagents safe?
19. How susceptible is the instrument to plugging?
20. Will the extractive materials of construction, etc., withstand corrosion?
21. Can the pumps withstand corrosion?
22. What is the size (cost of the basic replacement modules)?
23. What test points, diagnostics, decal information, troubleshooting procedures are provided to simplify diagnosis and repair?
24. What is the probability that the vendor will be able to service the equipment over its full design life?
25. What research and development capability does the vendor have in this product line?

TABLE 9-3

VENDORS OF DOUBLE-PASS TRANSMISSOMETERS

Cost Range $8000–$16000

Environmental Data Corp.
608 Fig Avenue
Monrovia, CA 91016

Lear Siegler, Inc.
74 Inverness Drive East
Englewood, CO 80110

Research Appliance Co. Chemed Corp. Route 8 Gibsonia, PA 15044	Same Instrument	Contraves Goerz Corp. 301 Alpha Drive Pittsburgh, PA 15238
Dynatron Inc. 57 State Street North Haven, CT 06473	Same Instrument	Western Precipitation Div. Joy Manufacturing Co. P.O. Box 2744 Terminal Annex Los Angeles, CA 90051

Esterline Angus (Marketing Durag Instrument-Germany)
Box 24000
Indianapolis, IN 46224

Datatest, Inc.
1117 Cedar Avenue
Croyden, PA 19020

TABLE 9-4

VENDORS OF SINGLE-PASS TRANSMISSOMETERS

Cost Range $800–$4000

Bailey Meter
29801 Euclid Avenue
Wickliffe, OH 44092

Cleveland Controls, Inc.
1111 Brookpark Road
Cleveland, OH 44109

De-Tec-Tronic Corp.
2512 N. Halsted Street
Chicago, IL 60614

Electronics Corp. of America
1 Memorial Drive
Cambridge, MA 02142

HABCO
85 Nutmeg Lane
Glastonbury, CN 06033

Leeds & Northrop
Sumneytown Pike
North Wales, PA 19454

Photomation Inc.
270 Polatis Avenue
Mountain View, CA 94042

Preferred Utilities Manufacturing
11 South Street
Danbury, CT 06810

Reliance Instrument Manufacturing
164 Garibaldi Avenue
Lodi, NJ 07644

Robert H. Wager
Passiac Avenue
Chatham, NJ 07928

TABLE 9-5

PRINCIPAL CONTINUOUS SOURCE MONITOR MANUFACTURER SUMMARY (JULY 1978)

Extractive Monitors

Instrument Vendor	Gases Measured					Measurement Range	Turnkey Systems	Approximate Cost in Thousands of Dollars
	SO_2	NO	NO_2	CO_2	CO			
Nondispersive Infrared Instruments								
Beckman	X	X		X	X	Various ranges in ppm or percent	Yes	3–5.4
Bendix	X	X		X	X	0.5 ppm – 50%	Yes	3–4 (I)
Esterline Angus	X	X		X	X	2 ppm – 100%		5
Horiba	X	X	X	X	X	10 – 2000 ppm		3–5
Infrared Ind.	X	X		X	X	200 ppm – 10%*		1–2
Leeds and Northrop	X			X		0 – 1000 ppm*	Yes	5.5 (I)
MSA	X	X		X	X	0 – 2000 ppm*	Yes	3–4 (I)
Teledyne				X	X	0 – 1000 ppm*	Yes	11–13(S)
Extractive Differential Absorption Instruments								
CEA	X	X			X	2–50,000 ppm		3–6
DuPont	X	X	X			1 ppm – 100%	Yes	13–23(S)
Esterline Angus	X		X				Yes	
Teledyne	X					2 ppm – 100%	Yes	12–14 (S)
Western	X	X	X		X	75–5000 ppm	Yes	12–22 (S)

(S) – System cost estimate by manufacturer on request
(I) – Instrument cost only; does not reflect system cost
* – Other ranges available upon request

TABLE 9-5

PRINCIPAL CONTINUOUS SOURCE MONITOR MANUFACTURER SUMMARY (JULY 1978)–Continued

Instrument Vendor	Gases Measured					Measurement Range	Turnkey Systems	Approximate Cost in Thousands of Dollars
	SO_2	NO	NO_2	CO_2	CO			
Fluorescence Instruments								
Research Appliance Corp.	X					1–5000 ppm		6
Thermo Electron Corp.	X					1–10,000 ppm		6–7
Chemiluminescence Instruments								
Beckman		X	X			0–9%		6.2
Bendix		X	X				Yes	(S)
McMillan Electronics		X	X					
Meloy		X	X			0–2000 ppm	Yes	5.4
Monitor Labs		X	X					
Scott		X	X			0–10,000 ppm		4–5
Source Gas Analyzers Inc.		X	X			0–3000 ppm		
Thermo Electron Corp.		X	X			5–10,000 ppm		5–6
Flame Photometric Instruments								
Meloy	X					25–10,000 ppm	Yes	3
Process Analyzers, Inc.	X					5 ppm – %		
Tracor	X							9

TABLE 9-5

PRINCIPAL CONTINUOUS SOURCE MONITOR MANUFACTURER SUMMARY (JULY 1978)—Continued

Instrument Vendor	Gases Measured						Measurement Range	Turnkey Systems	Approximate Cost in Thousands of Dollars
	SO_2	NO	NO_2	CO_2	CO	O_2			
Polarographic Instruments									
Beckman						X	0–25%		1–1.5
IBC/ Berkeley	X	X	X				0–10,000 ppm		2–5.5 (S)
Dyna- sciences	X	X	X		X	X	0.01–200,000 ppm	Yes	2–8 (S)
Interscan Corp.	X		X		X			Yes	1 (I)(S)
Teledyne						X	0–25%		1.5
Theta Sensors (MRI)	X		X			X	1–20,000 ppm		1–4
Western Precipi- tator (Joy)	X		X	X	X	X	0–1000 ppm		1.5
Electrocatalytic Instruments									
CEA						X	0–25%		
Dynatron						X	0–25%		
Lear Siegler						X	0–25%		4.5–5.8
MSA						X	0.1–20.8%		2
Teledyne						X	0–25%		1.5
Thermox						X	0–25%	Anubar Probes Available	2
Westing- house						X	0–25%		5

TABLE 9-5

PRINCIPAL CONTINUOUS SOURCE MONITOR MANUFACTURER SUMMARY (JULY 1978)—Continued

Instrument Vendor	Gases Measured						Measurement Range	Turnkey Systems	Approximate Cost in Thousands of Dollars
	SO_2	NO	NO_2	CO_2	CO	O_2			
Amperometric Instruments									
Barton ITT	X						0–1000 ppm		5
International Ecology Systems	X						0–10,000 ppm		5
Paramagnetic Instruments									
Beckman						X	0–25%		
MSA						X	0–25%		3
CEA						X			
SCOTT						X	0–100%		1–1.5
Leeds and Northrop						X		Yes	(S)
Taylor-Servomex						X	0–100%		1–1.5

TABLE 9-6

OXYGEN ANALYZER SUMMARY

Vendor	Analysis Method			Sampling Type	
	Paramagnetic	Polarographic	Electro-catalytic	In-Situ	Extractive
Astro			X	X	X
Beckman		X			X
Cleveland Controls	X		X	X	X
Corning			X	X	
Dyna-sciences		X			X
Dynatron			X	X	
Esterline Angus	X				X
Gas Tech		X			X
Hays-Republic			X	X	X
Joy		X			X
Lear Siegler			X	X	
Leeds and Northrop	X				X
Lynn		X			X
MSA	X		X		X
Scott	X				X
Taylor-Servomex	X				X
Teledyne		X			X
Thermox			X		X
Theta Sensors		X			X
Westinghouse			X	X	

TABLE 9-7

IN-SITU MONITOR SUMMARY

Vendor	Gases Measured					Method			Measurement Range	Approximate Cost in Thousands of Dollars
	SO_2	NO	CO_2	CO	O_2	Opacity	In-stack	Cross-stack		
CEA					X		X			
Contraves Goerz	X	X	X	X				X		30
Dynatron					X		X		0–25%	
Environmental Data Corp.	X	X	X	X		X		X	0–5000 ppm	20–40
Lear Siegler	X	X			X		X		0–500; 0–1000; 0–1500 ppm	4.5–17
Westinghouse					X		X			

TABLE 9-8

LIST OF INSTRUMENT MANUFACTURERS

MANUFACTURERS OF NDIR MONITORS

Positive Filtering Instruments	*Negative Filtering Instruments*
Beckman Instruments, Inc. 2500 Harbor Boulevard Fullerton, CA 92634	Bendix Corporation Process Instruments Div. P.O. Drawer 831 Lewisburg, WV 24901
Calibrated Instruments, Inc. 731 Saw Mill River Road Ardsley, NY 10502	Esterline Angus 19 Rozel Road Princeton, NJ 08540

TABLE 9-8

LISTS OF INSTRUMENT MANUFACTURERS—Continued

Positive Filtering Instruments	*Negative Filtering Instruments*
CEA Instruments (Peerless) 555 Madison Avenue New York, NY 10022	Leeds & Northrop Sumneytown Pike North Wales, PA 19454
Horiba Instruments, Inc. 1021 Duryea Avenue Santa Ana, CA 92714	MSA Instrument Division Mine Safety Appliances 201 Penn Center Boulevard Pittsburgh, PA 15208
Infrared Industries P.O. Box 989 Santa Barbara, CA 93102	Teledyne – Analytical Instruments 333 West Mission Drive P.O. Box 70 San Gabriel, CA 91776

MANUFACTURERS OF EXTRACTIVE DIFFERENTIAL ABSORPTION ANALYZERS

Teledyne – Analytical Instruments 333 West Mission Drive P.O. Box 70 San Gabriel, CA 91776	DuPont Company Instrument Products Scientific & Process Div. Wilmington, DE 19898
CEA Instruments 555 Madison Avenue New York, NY 10022	Esterline Angus 19 Rozel Road Princeton, NJ 08540
Western Research and Development Ltd. Marketing Department No. 3, 1313 – 44th Ave. N.E. Calgary, Alberta T2E GL5	

TABLE 9-8

LISTS OF INSTRUMENT MANUFACTURERS–Continued

MANUFACTURERS OF FLUORESCENCE SOURCE ANALYZERS

Thermo Electron Corporation
Environmental Instruments Div.
108 South Street
Hopkinton, MA 01748

MANUFACTURERS OF CHEMILUMINESCENCE ANALYZERS

Beckman Instruments, Inc.
Process Instruments Division
2500 Harbor Boulevard
Fullerton, CA 92634

Bendix Corporation
Process Instruments Division
P.O. Drawer 831
Lewisburg, WV 24901

McMillan Electronics Corporation
7327 Ashcroft
Houston, TX 77036

Meloy Laboratories, Inc.
6715 Electronic Drive
Springfield, VA 22151

Monitor Labs
4202 Sorrento Valley Boulevard
San Diego, CA 92121

Scott Environmental Systems Division
Environmental Tectonics Corporation
County Line Industrial Park
Southampton, PA 18966

Source Gas Analyzers, Inc.
7251 Garden Grove Boulevard
Garden Grove, CA 92641

Thermo Electron Corporation
Environmental Instruments Division
108 South Street
Hopkinton, MA 01748

TABLE 9-8

LISTS OF INSTRUMENT MANUFACTURERS—Continued

MANUFACTURERS OF FLAME PHOTOMETRIC ANALYZERS

Tracor, Inc.
Analytical Inst.
6500 Tracor Lane
Austin, TX 78721

Meloy Laboratories, Inc.
6715 Electronic Drive
Springfield, VA 22151

Process Analyzers, Inc.
1101 State Road
Princeton, NJ 08540

MANUFACTURERS OF POLAROGRAPHIC ANALYZERS

Dynasciences (Whitaker Corp.)
Township Line Road
Blue Bell, PA 19422

IBC/Berkeley Instruments
2700 DuPont Drive
Irvine, CA 92715

Western Precipitation Division
Joy Manufacturing Company
P.O. Box 2744 Terminal Annex
Los Angeles, CA 90051
(Portable models – not designed
for continuous stack application)

Beckman Instruments, Inc.
Process Instruments Division
2500 Harbor Boulevard
Fullerton, CA 92634
(O_2 only)

Gas Tech Inc.
Johnson Instrument Division
331 Fairchild Drive
Mountain View, CA 94043
(O_2 only)

Interscan Corp.
20620 Superior Street
Chatsworth, CA 91311

Theta Sensors, Inc.
Box 637
Altadena, CA 91001
(will provide systems)

Teledyne Analytical Instruments
333 West Mission Drive
San Gabriel, CA 91776
(O_2 only – micro-fuel cell)

Lynn Products Company
400 Boston Street
Lynn, MA 01905
(O_2 only)

TABLE 9-8

LISTS OF INSTRUMENT MANUFACTURERS—Continued

MANUFACTURERS OF ELECTROCATALYTIC OXYGEN ANALYZERS

Westinghouse Electric Corporation
Computer and Instrument Division
Orrville, OH 44667
(in-situ)

Lear Siegler, Inc.
Environmental Technology Division
74 Inverness Drive East
Englewood, CO 80110
(in-situ)

Dynatron, Inc.
Barnes Industrial Park
Wallingford, CT 06492

Teledyne Analytical Instruments
333 West Mission Drive
San Gabriel, CA 91776

Astro Resources Corp.
Instrument Division
P.O. Box 58159
Houston, TX 77573

Mine Safety Appliances
Instrument Division
201 Penn Center Boulevard
Pittsburgh, PA 15235
(extractive)

Thermox Instruments, Inc.
6592 Hamilton Avenue
Pittsburgh, PA 15206

Cleveland Controls, Inc.
1111 Brookpark Road
Cleveland, OH 44109

Corning Glass Works
Ceramic Products Division
Corning, NY 14803
(designed for [illegible]ass furnaces)

Hays-Republic
Milton Roy Company
4333 So. Ohio Street
Michigan City, IN 46360

MANUFACTURERS OF AMPEROMETRIC ANALYZERS

Barton ITT
Process Instruments and Controls
580 Monterey Pass Road
Monterey Park, CA 91754

International Ecology Systems
4432 North Kedzie Avenue
Chicago, IL 60625
(combined colorimetric method)

TABLE 9-8

LISTS OF INSTRUMENT MANUFACTURERS—Continued

MANUFACTURERS OF CONDUCTIMETRIC ANALYZERS

Calibrated Instruments, Inc.
731 Saw Mill Road
Ardsley, NY 10502

MANUFACTURERS OF PARAMAGNETIC ANALYZERS

Cleveland Controls, Inc.
1111 Brookpark Road
Cleveland, OH 44109

Scott Environmental Systems Division
Environmental Tectonics Corp.
County Line Industrial Park
Southampton, PA 18966

Taylor Servomex-Sybron Corp.
Analytical Instrument Division
Rochester, NY 14604

Mine Safety Appliances Co.
201 Penn Center Boulevard
Pittsburgh, PA 15235

Beckman Instruments, Inc.
Process Instruments Division
2500 Harbor Boulevard
Fullerton, CA 92634

Leeds and Northrop
Sumneytown Pike
North Wales, PA 19454

MANUFACTURERS OF CONDUCTIVITY ANALYZERS

Leeds and Northrop
Sumneytown Pike
North Wales, PA 19454

Esterline Angus
19 Rozel Road
Princeton, NJ 08540

MANUFACTURERS OF IN-SITU MONITORS

Cross-Stack

Environmental Data Corporation
608 Fig Avenue
Monrovia, CA 91016

Contraves Goerz Corporation
610 Epsilon Drive
Pittsburgh, PA 15238

TABLE 9-8

LISTS OF INSTRUMENT MANUFACTURERS–Continued

MANUFACTURERS OF IN-SITU MONITORS–Continued

In-Stack

Lear Siegler, Inc.
Environmental Technology Division
74 Inverness Drive East
Englewood, CO 80110

Oxygen Monitors Only

Westinghouse Electric Corporation
Computer and Instrument Division
Orville, OH 44667

Dynatron, Inc.
Barnes Industrial Park
Wallingford, CT 06492

Cleveland Controls, Inc.
1111 Brookpark Road
Cleveland, OH 44109

Corning Glass Works
Ceramic Products Division
Corning, NY 14803

Hays-Republic
Milton Roy Company
4333 So. Ohio Street
Michigan City, IN 46360

9.2 Vendors of Recording Instrumentation

Although there are many manufacturers of strip chart recorders, there are a few firms that tend to dominate sales in industrial applications. A sampling of these is given in Table 9-9.

There are over 50 manufacturers of data-logging type equipment. Those most frequently encountered in air pollution applications are given in Table 9-10. Vendors of data processors designed for continuous stack emission data are given in Table 9-11.

TABLE 9-9

MANUFACTURERS OF STRIP CHART RECORDERS

Beckman Instruments
Process Instruments Division
2500 Harbor Boulevard
Fullerton, CA 92634

Esterline Angus Instr. Corp.
An Esterline Company
1201 Main-Box 24000
Indianapolis, IN 46224

The Foxboro Co.
38 Neponset Avenue
Foxboro, MA 02035

Gulton Industries Inc.
Measurement-Control
Systems
Gulton Industrial Park
East Greenwich, RI 02818

Hewlett-Packard
Scientific Instruments Division
1601 California Avenue
Palo Alto, CA 94304

Honeywell Inc.
Process Control Division
1100 Virginia Drive
Fort Washington, PA 19034

Leeds & Northrop Co.
Sumneytown Pike
North Wales, PA 19454

Westinghouse Electric Co.
Product Info Center
Westinghouse Building
Gateway Center
Pittsburgh, PA 15222

TABLE 9-10

MANUFACTURERS OF DATA LOGGING EQUIPMENT

Acurex Corporation
Autodata Division
485 Clyde Avenue
Mountain View, CA 94042

Datel Systems, Inc.
1020 Turnpike Street
Canton, MA 02021

Doric Scientific
Division of Emerson Electric
3883 Ruffin Road
San Diego, CA 92123

Esterline Angus
Instrument Corp.
Box 24000
Indianapolis, IN 46224

Monitor Labs, Inc.
4202 Sorrento Valley Boulevard
San Diego, CA 92121

Zonics, Inc.
6862 Hayvenhurst Avenue
Van Nuys, CA 91406

TABLE 9-11

MANUFACTURERS OF CONTINUOUS MONITOR DATA PROCESSORS

Acurex Corporation
485 Clyde Avenue
Mountain View, CA 94042
(Autodata Nine CSM)

E.I. DuPont DeNemours & Co., Inc.
Instrument Products Division
Wilmington, DE 19898
(463 Emission Monitoring System
Data Processor – Part of Total
Monitoring DuPont Systems)

Bendix
Process Instruments Division
P.O. Drawer 831
Lewisburg, W VA 24901
(Model 9000 Analyzer Control)

Electro Scientific Industries, Inc.
13900 NW Science Part Drive
Portland, OR 97229
(Model ESI-6000)

Esterline Angus
P.O. Box 24000
Indianapolis, IN 46224

Environmental Data Corp.
608 Fig Avenue
Monrovia, CA 91016
(EDC-3110 Data Systems)

Lear Siegler, Inc.
Environmental Technology Division
74 Inverness Drive East
Englewood, CO 80110
(DP-30 Data Processor)

Dynatron, Inc.
Barnes Industrial Park
Wallingford, CT 06492

Dynasciences
Township Line Road
Blue Bell, PA 19422
(Model 6043 Prog. Data Acquisition
System)
(Computing Limits Reporter
Model 6000)

9.3 Bibliography

There have been a number of articles published that deal with the evaluation or comparison of source monitors. Unfortunately, many of these publications are misleading. A number of them have been written by instrument vendors wishing to publicize their product line. Others have been written with a particular bias in mind, where the author may be attempting to show that no monitor operates properly, or that monitors can do more than they are capable of. Another problem is that the experiments performed to evaluate a number of systems often have been poorly designed or have suffered because of a lack of funding and time. The evaluation of these systems under field conditions is an expensive and tedious procedure; very few good field comparison tests have actually been done. Also, many of the articles referenced in this section are now dated. The work described involves monitors that are no longer marketed, and conclusions reached for a given model of an instrument are no longer applicable, since the model may have been modified since the test.

These references, however, can give a broader perspective to the reader of some of the problems that may be encountered in selecting, installing, and operating a continuous monitoring system. Specific articles, applicable to the reader's application, should be obtained to give insights into possible problems. The articles, however, should be read critically.

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CHAPTER 10

APPLICATIONS OF CONTINUOUS MONITORS

10.1 Introduction

A continuous source monitor can provide both industry and regulatory agencies with numerous tangible benefits. A properly installed and operated continuous monitoring system can yield a large amount of data on source emissions. This information is beneficial, since it establishes a reliable foundation upon which important decisions can be made. The following sections illustrate and explain the various advantages of accurate continuous monitoring data for both the plant and the agency.

10.2 Advantages of Monitoring Data to the Source

A well-designed and maintained continuous monitoring system supplies the source operator with valuable information. It provides data on the operation of the industrial process in addition to data on the process emissions to the atmosphere. It can be viewed as a money-saving process control tool for evaluating source operating efficiency. The monitor allows the source operator to assess process variables so that emissions can be held to a minimum, maximizing product output with reduced fuel consumption. A good example would be the use of a sulfur dioxide monitor at a sulfuric acid plant. The analyzer would give the operator a continuous record of SO_2 lost to the atmosphere. The plant engineer then would be able to use this information to regulate the process and to evaluate process efficiency with a possible reduction in fuel usage or raw material loss.

The continuous monitoring system also can be used to determine maintenance needs for process and emissions control equipment. The monitor data can be useful in determining the operating efficiency of key process equipment and emissions control systems. The maintenance necessary for these pieces then can be performed according to indicated need rather than a rigid periodic schedule. This could extend the operating life of some equipment or indicate the necessity of maintenance for equipment that is not operating properly under the routine schedule. The upkeep of process and control equipment can be done, therefore, on a more cost-effective basis. For example, opacity monitors have been used to diagnose and tune electrostatic precipitators, and continuous SO_2 monitors have been used to tune flue gas desulfurization processes.

A continuous monitor also is applicable to process and control equipment design and evaluation. The continuous analyzer gives the most accurate data on source operation and emissions available. This information is a valuable factor in evaluating the performance of emission control equipment at the source. Analyzer data yield a record of control equipment efficiency over a much longer period of time than a manual stack test. The data are truer indicators of the equipment's effectiveness in reducing emissions. The user would be able to evaluate manufacturer contractual obligations thoroughly for equipment performance and perhaps avoid the many past problems that have arisen. Designers would be able to use these data to improve control and process equipment design. Monitor data analysis also may help a source operator reach optimum conditions for all source operations. The potential benefits derived from using monitor data for these purposes have not yet been fully evaluated.

The plant's managerial staff could find that an unanticipated benefit from a continuous monitoring system is a reduction in problems associated with meeting emission regulations. The monitor could give a valid record of source emissions that would aid in making decisions for source regulatory compliance. This would help relieve the ambiguous situations sometimes created by manual stack testing. It also could act as a safeguard in refuting false charges of high emissions from a regulatory agency or local citizens (see Ref. 2 of Section 2.4). These points alone would be sufficient justification for monitor installation at a source.

10.3 Advantages of Monitoring Data for the Regulatory Agency

The continuous monitor data gathered from sources greatly improve the enforcement abilities of a regulatory agency. A continuous monitoring system can provide a full-time data base for use by the agency in evaluating source compliance with regulations. These data reflect the actual operating conditions at the source and its emissions to the atmosphere. Continuous data, therefore, yield a much more accurate assessment of source compliance than the information generated during short-term manual stack testing at optimum source conditions. The agency is then able to develop more realistic, fairer regulations on emissions to the atmosphere. This situation ultimately would benefit the industrial source and the agency.

The regulatory agency can use the data to assist several other agency functions, for example:

- As a screening tool to identify the need for source inspections, visible emissions observations, etc.

- As a valuable source of information on nuisance conditions in an area.

- To pinpoint the nuisance and prove that a nuisance condition exists or to settle disputes between industry and community factions on the origin of the nuisance.

- For developing regional emission control strategies that evaluate the short-term impact of source emissions on air quality.

- To augment visible emissions observations.

- To provide input to episode control plans, improving episode control capabilities.

- To improve agency ability to relate effects of source emissions to ambient air quality with dispersion modeling.

10.4 Continuous Monitoring: Aid to Manual Source Sampling

A continuous monitoring system gives the plant and the agency a useful measure of manual stack test validity. The compliance tests require that data be obtained using manual reference methods. These methods may be subject to error from sampling mistakes or source fluctuations. A continuous emissions monitoring system can serve as a cross-check of manual reference method data. These two sets of data on source emissions can:

- Confirm validity of sampling results
- Point out possible errors in either manual or instrument measurements
- Help locate where errors may have taken place
- Assist in correcting problems in manual or instrument measurements

The continuous monitor is required for new sources; therefore, it can serve the above purposes with no additional cost.

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CHAPTER 11

THE PERFORMANCE SPECIFICATION TESTS*

11.1 Introduction

Continuous monitoring instruments installed at an affected facility must pass the Performance Specification Test requirements given in Part 60, Appendix B, of the Code of Federal Regulations. These tests evaluate the performance characteristics of opacity, SO_2, NO_x, and O_2 or CO_2 continuous monitors. This discussion presents the major considerations involved in carrying out the specification tests and the methods of data calculation. Appendix B of 40 CFR 60 is reproduced in Appendix D of this handbook. Some practical suggestions and comments for performing the specification tests also are included to aid in planning and conducting such a test.

11.2 Performance Specification Test 1 – Transmissometer Systems

11.2.1 General

Transmissometers installed at an affected facility must meet design and specification requirements given in Performance Specification Test 1. Instruments installed prior to the proposal date of the CFR subpart addressing the source category may be requested by the EPA Administrator to demonstrate acceptability for continuous monitoring applications.

11.2.2 Transmissometer Design Criteria

Performance Specification Test 1 establishes required EPA instrument design criteria for transmissometers. These have been discussed in Chapter 4 of this handbook.

If measurements of the design specifications are made by personnel at the facility, all measurements must be recorded and reported to the Administrator. The projection and view tests need not be performed by the source operator if the analyzer and optics are certified by the manufacturer to conform to design specifications. Results of manufacturer tests must be reported to the Administrator by the source operator.

The transmissometer specification test includes design criteria for instrument calibration error. The calibration error tests in Performance Specification Test 1 are especially important, since there is no practical manner in which the relative accuracy of a transmissometer can be determined after it has been installed. The,other Performance Specification Tests check the relative accuracy of monitoring instruments against the values of reference methods 3, 6, or 7 obtained by manually sampling the stack gas. The opacity reference method 9 is not used to check relative accuracy of transmissometer instruments. The instrument calibration error test then becomes very important.

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*The Performance Specification Tests are currently undergoing revision by EPA. Further information on these revisions may be obtained by referring to Stack Sampling News, Volume 7, No. 2, February 1979, pp. 2-3 and references therein.

The transmissometer calibration error test may be performed by the manufacturer prior to shipment or by the source before the instrument is installed on the stack. Proper notification of this test must be given to the agency in either case. The response time of the instrument also is determined during the calibration error test. The instrument must be set up for the monitor pathlength to be used on the stack. All of the manufacturer's written instructions for initial operation and calibration are to be performed. The calibration test is then performed using three neutral density filters corresponding to low-, mid-, and high-span range as specified for the facility in the Part 60 subparts. The table of filter opacity and optical density required for a given span range as found in the Federal Register is given in Table 11-1.

TABLE 11-1

NEUTRAL DENSITY FILTERS FOR TRANSMISSOMETER CALIBRATION ERROR

Span Value* (percent opacity)	Calibrated Filter Optical Densities with Equivalent Opacity in Parentheses		
	Low-range	Mid-range	High-range
50	0.1 (20)	0.2 (37)	0.3 (50)
60	0.1 (20)	0.2 (37)	0.3 (50)
70	0.1 (20)	0.3 (50)	0.4 (60)
80	0.1 (20)	0.3 (50)	0.6 (75)
90	0.1 (20)	0.4 (60)	0.7 (80)
100	0.1 (20)	0.4 (60)	0.9 (87-1/2)

*That span value given in the Subpart of Part 60, Title 40 of the CFR for a specific source category.

It should be noted that the table is written around a single-pass instrument and should be interpreted in terms of stack exit opacity. The filters used in the test must be certified by the manufacturer to be within ±3 percent of the recorded filter value. It is recommended that all filters be checked for true opacity on a well-collimated photopic transmissometer (view and projection angle of 1 degree). The most stable filters are made of stainless steel wire mesh. These supply a true neutral density without decomposition. The glass or gelatin filters can decompose, changing opacity value in addition to permitting the transmittance of infrared radiation. All filters used in the calibration error test must be large enough to block the entire optical volume of the transmissometer.

Instrument calibration error is determined by inserting each of the three filters (low-, mid-, and high-range) into the middle of the optical path of the transmissometer. A total of five nonconsecutive readings for each filter is made with data recorded in percent opacity. The calibration error for each of the 15 readings is calculated:

$$\text{Transmissometer opacity reading} - \text{Known filter opacity reading} = x_i \text{ difference } (+ \text{ or } -)$$
$$i = 1 \text{ to } 15$$

The data gathered from this test will be used in calculating the sum of the absolute mean difference and the confidence interval for each of the three filters. A complete explanation of these calculations will be given in the performance specification calculation section.

The instrument response time tests are made at this time using the high-range neutral density filter. After proper instrument zero and span have been completed, the high-range filter is inserted in the instrument optical path. The time needed for the instrument to reach 95 percent of the filter range value is recorded, and the reading is allowed to stabilize at the full filter span value. The high-range filter then is removed from the optical path and the time required for the instrument to come to within 95 percent of zero is recorded. This procedure is repeated for a total of five sets of span and zero readings. The mean response time is calculated:

$$\frac{\text{Sum of the 5 upscale and 5 downscale times}}{10} = \text{mean response time}$$

The mean response time must be no greater than 10 seconds.

11.2.3 Performance Specification Test 1

The Performance Specification Test evaluates the monitoring system location on the stack, the operating characteristics, and the data recording ability. The performance specifications for a continuous opacity monitor are given in Table 11-2.

TABLE 11-2

OPACITY MONITORS PERFORMANCE SPECIFICATIONS

Calibration error	≤3% opacity*
Zero drift (24 hr)	≤2% opacity*
Calibration on drift (24 hr)	≤2% opacity*
Response time	10 sec (maximum)
Operation test period	168 hr

*Expressed as the sum of the absolute value and the 95-percent confidence interval.

Instrument response time and calibration error for an opacity monitor are determined before stack installation. The other specifications are evaluated while the instrument is operating on the stack. Proper installation of the opacity monitor must be made following Federal Register guidelines before the drift tests are performed.

An opacity monitor must be located across a duct or stack section that provides a particulate matter flow through the instrument optical volume representative of the particulate matter flow through the entire duct. The transmissometer must be downstream of all particulate control devices and as far as possible from bends or obstructions in the duct. The most suitable location would be at least 8 duct diameters downstream of any flow disturbance. A transmissometer located after a bend is to be located in the plane defined by the bend (when possible). The instrument pathlength should include the entire duct diameter. A shorter monitor pathlength requires extra caution in locating the instrument for representative readings. The Administrator may require that the owner or operator of the opacity monitor demonstrate that the instrument location provides representative opacity readings.

The monitor optical and zero alignments are checked after the monitor is installed at the selected location. The optical alignment of the transmissometer light source and reflector or photodetector (for single-pass instruments) should be checked following the manufacturer's instructions. Instrument zero alignment is determined with a clean stack after the monitor mounting is mechanically stable (i.e., no duct thermal expansion or contraction). The internal instrument zero is then balanced to coincide with the actual zero check performed across the clean stack. These optical and zero alignment checks must be performed once a year.

Final instrument alignment is made after the facility has returned to normal operation. The optical alignment is rechecked as specified by the manufacturer. If the alignment has shifted, it must be readjusted. Any shifts in opacity measurements attributable to realignment are to be recorded and reported to the Administrator. A situation in which alignment shift can occur may not produce significant shifts in opacity measurements if the plant operating parameters change within a constant and adequately narrow range. The Administrator may require the transmissometer to be moved or mounted on more stable structures if these problems become significant.

In the Performance Specification Test, the instrument is conditioned for 168 hours after installation. During the conditioning period, the instrument is operated in a normal manner. Necessary repairs and adjustments are allowed so that the instrument may be brought into proper operation.

11.2.4 Zero and Calibration Drift Tests

The zero and calibration drift tests are conducted during the 168-hour operational test period. The opacity monitoring system is operated continuously for 168 hours after the completion of the conditioning period. The instrument must monitor the effluent at all times during the operational test period except when it is being zeroed and calibrated. The instrument electronic components, including light source and photodetector, simulated zero, and up-scale opacity calibration, must be checked at 24-hour intervals. The transmissometer must be zeroed and calibrated on a daily basis. The zero setting (on the recorder only) must be offset 10 percent to account for possible negative drift. All exposed optical surfaces must be cleaned and optical alignment must be checked each 24 hours. Note that this conflicts with the requirement of Paragraph 9.2.8 of Performance Specification 1, which disallows cleaning during the specification test if it is not part of normal operating procedure. (A decision will most likely be required for this situation by the agency representative observing the test.) Manufacturer recommendations may be followed for these procedures provided they meet or exceed the Federal specifications. Automatic instrument corrections (no operator intervention) are allowed at any time.

The data recorded at each 24-hour interval includes the zero and upscale calibration readings after system calibration (set at the same values each 24-hour interval). The zero reading is recorded after 24 hours of instrument operation but before cleaning or adjustment of the instrument zero. The instrument calibration reading is recorded after cleaning the optical surfaces and resetting the zero adjustment but before resetting the calibration adjustment. These data are used in calculating individual differences (x_i) used in the calculation of the 95-percent confidence interval and absolute mean value.* The zero drift x_i values are calculated:

$$\left(\begin{array}{c}\text{Zero readings after}\\ \text{cleaning optics}\end{array}\right) - \left(\begin{array}{c}\text{Zero reading before}\\ \text{cleaning optics 24 hours later}\end{array}\right) = x_i \ (+ \text{ or } -)$$

Calibration drift x_i values are:

$$\left(\begin{array}{c}\text{Calibration reading after}\\ \text{cleaning optics and}\\ \text{zero adjustment}\end{array}\right) - \left(\begin{array}{c}\text{Calibration reading after cleaning}\\ \text{optics and zero adjustment}\\ \text{but before calibration}\\ \text{adjustment 24 hours later}\end{array}\right) = x_i \ (+ \text{ or } -)$$

The sum of the absolute mean value and the 95-percent confidence interval is computed separately for zero drift and calibration drift, then reported. The absolute mean value is found:

$$\left|\overline{x}\right| = \frac{1}{n} \sum_{i=1}^{n} x_i$$

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*See Appendix B for a further discussion of the statistical methods used in the Performance Specification Tests.

where:

n = number of data points

x_i = difference (+ or -)

$|\bar{x}|$ = absolute mean value

and the 95-percent confidence interval is:

$$C.I._{95} = \frac{t_{0.975}}{n\sqrt{n-1}} \sqrt{n\,(\Sigma x_i{}^2) - (\Sigma x_i)^2}$$

where:

n = number of data points

x_i = difference (+ or −)

$t_{0.975}$ = the t value derived in the t test corresponding to the probability that a measured value will be within 95 percent of the true value

$C.I._{95}$ = 95-percent confidence interval estimate of the mean value

TABLE 11-3

VALUES FOR $t_{0.975}$

n	$t_{0.975}$	n	$t_{0.975}$
2	12.706	10	2.262
3	4.303	11	2.228
4	3.182	12	2.201
5	2.776	13	2.179
6	2.571	14	2.160
7	2.447	15	2.145
8	2.365	16	2.131
9	2.306		

For example, the zero drift is computed by taking the zero reading differences (x_i) and adding them together according to their sign value (see Table 11-4).

TABLE 11-4

24-HOUR TRANSMISSOMETER ZERO DRIFT DATA

24-Hour Interval	x_i Value	x_i^2
1	−1	1
2	0	0
3	−2	4
4	+1	1
5	0	0
6	+2	4
7	−1	1
Σx_i	−1	11

Then using the Σx_i in the equation for the absolute mean value:

$$\left|\bar{x}\right| = \frac{1}{n}\sum_{i=1}^{n} x_i = \frac{-1}{7} = \left|0.143\right|$$

The confidence interval is then calculated:

$$C.I._{95} = \frac{t_{0.975}}{n\sqrt{n-1}}\sqrt{n\,(\Sigma x_i^2) - (\Sigma x_i)^2}$$

$$= \frac{2.447}{7\sqrt{7-1}}\sqrt{7\,(11) - (1)} = 1.244$$

The sum of the absolute mean value and the 95-percent confidence interval is reported as zero drift:

$$\left|\bar{x}\right| + C.I._{95} = 0.143 + 1.244 = 1.387 \text{ zero drift}$$

The preceding calculations also are made for the calibration error tests (each of the three filters used) and calibration drift using the x_i values found in each test. The statistical basis for these calculations is given in Appendix B.

11.3 Performance Specification Test 2 – SO_2/NO_x Systems

11.3.1 General

Performance Specification Test 2 gives the installation requirements, test procedures, and data calculation methods for evaluating the acceptability of a continuous SO_2/NO_x monitoring system. This performance specification procedure does not prescribe specific instrument design criteria. However, reference methods 6 and 7 are conducted concurrently with the monitor evaluation to determine the monitor's relative accuracy.

Performance Specification Test 2 requires the advance preparation of instrument calibration gas mixtures and the reference method test equipment. The calibration gases used during the Performance Specification Test are:

- Zero gas certified by the manufacturer to contain less than 1 ppm of the pollutant gas to be measured. Ambient air may be used as zero gas (depending on instrument requirements).
- Sulfur dioxide (SO_2) gas mixtures may be in air or nitrogen.
- Nitrogen dioxide (NO_2) gas mixtures must be in air.
- Nitric oxide (NO) gas mixtures must be in an oxygen free (<10 ppm) inert gas.

The two gas concentrations for the performance test must be approximately 50 percent and 90 percent of the span values as given in the subparts. A listing of calibration gas concentrations given in the subparts for a fossil-fuel steam generating facility is shown in Table 11-5. Refer to the subparts for calibration values at other types of facilities.

All calibration gas concentrations must be checked by triplicate reference method gas analysis. The three test analyses results are averaged. Individual tests must agree within ±20 percent of the average gas concentration or the analysis must be repeated. The analyses are to be performed on the calibration gas no more than 2 weeks prior to use in the specification tests.

The recommended equipment for reference method testing of SO_2/NO_x stack gas concentration is:

- Method 6 – Reference Method for SO_2 (Reference Method 8 is used to measure SO_2 in Sulfuric Acid Plants)
  - Calibrated control console – pump, flow meter, and dry gas meter
  - Three heated gas sampling probes
  - Data sheets

TABLE 11-5

SPAN AND CALIBRATION GAS VALUES

Gas Monitored	Type of Fossil Fuel	Span Value	Calibration Gas Value	
			50% of Span Value	90% of Span Value
SO_2	Liquid Solid	1000 ppm 1500	500 ppm 750	900 ppm 1350
NO_x	Gas Liquid Solid	500 ppm 500 1000	250 ppm 250 500	450 ppm 450 900
O_2	–	1.5-2.5 normal source conc.	0.50 Span Value	0.90 Span Value Or ambient if span >21%
CO_2	–	1.5-2.5 normal source conc.	0.50 Span Value	0.90 Span Value

- Minimum of 11 midget impinger sampling trains
- Fresh reagents
  - 80 percent isopropyl alcohol (tested for oxidant contamination)
  - 3 percent hydrogen peroxide (H_2O_2)

- Method 7 – Reference Method for NO_x
  - Minimum 30 gas sampling flasks (2 liter)
  - Three heated gas sampling probes
  - Pressure gage (0 to 30-inch Hg)
  - Pump (capable of >30-inch Hg suction)
  - Data sheets

Performance Specification Test procedures do not specifically state that the reference methods be conducted for a source compliance test. It is recommended however, that reference methods rather than equivalent methods be used whenever possible.

11.3.2 Monitor Location and Installation

The SO_2/NO_x continuous gas monitor must be located at a sampling point where measurements can be made which are directly representative or can be corrected to be representative of the total emissions. The Federal Register establishes requirements for the location and installation of extractive and in-situ-type monitors at a source. The requirements are:

- Stack gases may be assumed to be nonstratified at any point greater than 8 duct diameters downstream of air in-leakage.
- This assumption on stratification may not be made for sampling locations upstream of an air preheater at a steam-generating facility.
- For sampling points located where the gas is assumed or demonstrated to be nonstratified, extractive or in-situ monitors may sample at a point of average concentration.
- Extractive sampling points must be no closer than 1 meter to the stack wall.
- Multipoint extractive sampling probes may be located at any points necessary to obtain consistently representative gas samples.
- Sampling locations at which gases are stratified must employ extractive sampling systems or in-situ sampling locations that obtain results that are consistently representative or can be corrected to be representative of the total emissions from the affected facility.
- The extractive type of system may accomplish this requirement by using a multipoint sampling probe. The in-situ monitor must be located so that its optical path will view a representative gas sample.
- It must be demonstrated that sampling at stratified gas locations gives consistent readings for several plant operating conditions (i.e., points of average concentration do not shift with operating changes).
- Pollutant and diluent gas monitoring systems should be of the same type – both extractive or in-situ. If the systems are of different types, the extractive system must use a multipoint sampling probe.
- Temperature, velocity, and gas concentration traverses of the stack gas may help to characterize gas stratification. If no stratification is shown at a point less than 8 duct diameters downstream of air in-leakage, procedures for sampling nonstratified gas may be used.

11.3.3 Specification Test Procedures

The test procedures given in Performance Specification Test 2 are designed to evaluate the continuous monitor operating performance. The required instrument performance specifications are given in Table 11-6.

TABLE 11-6

PERFORMANCE SPECIFICATIONS FOR SO_2/NO_x SYSTEMS

Parameter	Specification
Accuracy*	$\leq$20% of the mean value of the reference method test data
Calibration error*	$\leq$5% of each (50% of span, 90% of span) calibration gas mixture or internal calibration cell value
Zero drift (2 hr)*	2% of span
Zero drift (24 hr)*	2% of span
Calibration drift (2 hr)*	2% of span
Calibration drift (24 hr)*	2.5% of span
Response time	15 min maximum
Operational period	168 hr minimum

*Expressed as sum of absolute mean value plus 95-percent confidence interval of a series of tests.

An important note to Table 11-6 is made in the Federal Register for NO_x monitoring instruments that oxidize NO to NO_2. The monitor response-time test for instruments including this conversion for NO_x analysis must be performed using NO span gas. The requirements of Table 11-6 apply to both extractive- and in-situ-type monitors. The monitoring system is evaluated during the 168-hour operational test period, which begins after an initial 168-hour conditioning period. During the conditioning period, the monitor is thoroughly checked out and adjusted. In the operational test period, the only adjustments allowed are zero and calibration adjustment at 24-hour intervals and automatic instrument operations.

11.3.4 Calibration Error Test Procedures

The calibration error test is conducted on the completely assembled continuous monitoring system. The test may be performed with the monitoring system either installed on the stack (which is the preferred technique), or in the laboratory. Any difficulties with the monitoring system would present themselves for correction if it is installed at the stack prior to the calibration error test. Monitor state of the art at this time is such that it may be assumed that the instrument can meet specification requirements in the laboratory. Performing the calibration error test as the system is installed at the facility provides a means of troubleshooting the system in addition to giving a truer evaluation of instrument field operations.

The calibration error test may be performed during the conditioning period or the operational test period. The instrument start-up and initial calibration are performed following the manufacturer's written instructions. After the instrument has stabilized, 15 nonconsecutive measurements are made during zero gas, 50 percent, and 90 percent span gases. The zero gas is injected into the system for a zero reading (with 10-percent zero offset), then the calibration gases are injected (i.e., 0 percent, 50 percent, 90 percent, 0 percent, 50 percent, 90 percent, 0 percent, 50 percent, 90 percent, etc...). A nonextractive, in-situ monitor instead may perform this test using two calibration gas cells with manufacturer certified gas concentrations equivalent to 50-percent and 90-percent calibration gas requirements. All data must be recorded in concentration units (ppm). The difference between the calibration gas concentration and instrument readings (ppm), for each of the five measurements made on a calibration gas, is used for calculating the sum of the absolute mean value $|\bar{x}|$ and 95-percent confidence interval (C.I.$_{95}$). The calibration error for each gas is determined:

$$\frac{|\bar{x}| + \text{C.I.}_{95}}{\begin{array}{c}\text{Average calibration gas}\\ \text{concentration (ppm)}\end{array}} \times 100 = \text{Calibration Error}$$

The following example illustrates these calculations for a sulfur dioxide instrument and a 50-percent calibration gas. All of the calculations would be performed for the 90-percent calibration gas using the five readings obtained during the calibration error test.

Example 50-percent calibration gas:

Reference Method Average Concentration = 550 ppm

Calibration Error Test Data (extracted from table of 15 readings)

Reading No.	Calibration Gas Concentration (ppm)	Instrument Readings (ppm)	Difference (x_i) Instrument Reading Minus Calibration Gas Value	x_i^2
2	550	558	+8	64
5	550	560	+10	100
7	550	562	+12	144
8	550	547	−3	9
12	550	548	−2	4
			Σx_i +25	Σx_i^2 321

The absolute mean value $|\bar{x}|$ is calculated:

$$|\bar{x}| = \frac{1}{n} \sum_{i=1}^{n} x_i$$

$$|\bar{x}| = \frac{1}{5}(+25) = |5|$$

The 95-percent Confidence Interval (C.I.95) is calculated:

$$C.I._{95} = \frac{t_{0.975}}{n\sqrt{n-1}} \sqrt{n\ (\Sigma x_i^2) - (\Sigma x_i)^2}$$

$$C.I._{95} = \frac{2.776}{5\sqrt{5-1}} \sqrt{5\ (321) - (625)} = 8.690$$

The calibration error is:

$$\frac{|\bar{x}| + C.I._{95}}{[SO_2]\ ppm} \times 100$$

$$\frac{5 + 8.690}{550} \times 100 = 2.489\%$$

11.3.5 Response Time Test

The monitor response-time test and all other specification test procedures are conducted during the 168-hour operational test period. The response-time test evaluates the response time of the entire continuous monitoring system as installed. All system parameters, such as gas flowrate, sample line size, pump rates, and pressures, must be operated at normal system settings as given in the manufacturer's written instructions. Calibration gas injection must not change the normal system operating pressure.

The response-time test measures the time it takes the monitor to reach 95 percent of the final stable response when calibration gas and zero gas are quickly switched into the system. The test is carried out by injecting zero gas into the sampling interface allowing the monitor to reach a stable reading. Calibration gas of known concentration is then quickly switched into the system (50 percent or 90 percent gases may be used). (The 90-percent gas is recommended over the 50-percent gas for response-time test.) The time from injection to the time the instrument shows 95 percent of final stable response is recorded. Zero gas is reinjected into the sampling interface after the upscale reading has stabilized. The time from zero-gas injection to the time to reach 95 percent of final stable instrument response is recorded. The entire procedure is repeated three times. An in-situ, nonextractive monitor would perform these functions by inserting the highest calibration gas cell available. The average of the three upscale readings and average of the three downscale readings are taken with response time reported as the slower time. The upscale and downscale times must not differ more than 15 percent of the slower time:

$$\left[\begin{array}{c}\text{\% deviation from} \\ \text{slower system} \\ \text{average response}\end{array}\right] = \left[\frac{\left(\begin{array}{c}\text{average upscale} \\ \text{response time}\end{array}\right) - \left(\begin{array}{c}\text{average downscale} \\ \text{response time}\end{array}\right)}{\text{(slower time)}}\right] \times 100$$

11.3.6 Field Relative Accuracy Test

The relative accuracy of the continuous monitoring system is determined by comparing the instrument pollutant concentration measurements to the manual reference method analysis of the pollutant concentration in the stack gas. The Performance Specification Test 2 regulations require that nine consecutive sets of reference method data be taken with no more than one data set per hour. The sulfur dioxide data would then consist of nine applicable reference method tests: one reference method performed each hour for 9 hours. The oxides of nitrogen tests require a total of 27 NO_x reference method tests, which are divided into nine sets, three tests per set. The three individual NO_x reference method tests are to be performed concurrently or within a 3-minute interval; no more than one set (three tests) are to be made in 1 hour. The results of the three tests are averaged and the average is used in the calculations. The probe tip for the reference method tests described must be as close to the sampling location (extractive or in-situ) of the monitor as possible. The analyzer must continuously monitor stack gas pollutant concentrations during reference method testing. The average analyzer pollutant concentration measurements for each test period are determined by integrating or averaging the monitor data for each period. All data for the reference methods and the continuous monitor must be given on a consistent base (wet or dry). A moisture correction factor must be applied to data that are not on a consistent base. The moisture correction factor is determined by running concurrent reference method 4 tests with the other reference method tests. Reference method data are converted to parts per million in the following manner:

Dry Basis at Standard Conditions:

$$\text{ppm} = \frac{\text{gm/dm}^3 \times 24.06 \times 10^3}{\text{molecular weight (gm)}}$$

Wet Basis at Standard Conditions:

$$\text{ppm} = \frac{\text{gm/dm}^3 \times 24.06 \times 10^3}{\text{molecular weight (gm)}} \; (1-B_{ws})$$

where B_{ws} is the moisture fraction of the stack gas.

The difference between each test period instrument pollutant concentration (ppm) and the reference method concentration (ppm) is used in calculating the sum of the absolute mean value and 95-percent confidence interval for each pollutant (NO_x and SO_2).

$$\begin{pmatrix}\text{instrument test period}\\ \text{average (ppm)}\end{pmatrix} - \begin{pmatrix}\text{reference method}\\ \text{(ppm)}\end{pmatrix} = x_i \text{ (+ or -)}$$

The sum of the absolute mean value and the confidence interval divided by the average reference method gas concentration gives the relative accuracy of the instrument:

$$\left[\frac{|\bar{x}| + C.I._{95}}{\text{average reference method (ppm)}}\right] \times 100 = \%\text{ relative accuracy}$$

The following example illustrates the calculation of relative accuracy (all data have been expressed in ppm on a dry basis).

CALCULATION OF RELATIVE ACCURACY

Test No.	SO_2 Sample (ppm)	NO_x Sample (ppm) Average of 3 tests	Analyzer 1 hour Average (ppm)		Difference (x_i) (ppm)		x_i^2	
			SO_2	NO_x	SO_2	NO_x	SO_2	NO_x
1	417	614	398	602	−19	−12	361	144
2	430	572	409	602	−21	+30	441	900
3	429	624	404	638	−25	+14	625	196
4	429	614	400	655	−29	+41	841	1681
5	429	723	404	744	−25	+21	625	441
6	446	709	429	744	−17	+35	289	1225
7	450	696	438	744	−12	+48	144	2304
8	436	699	422	744	−14	+45	196	2025
9	410	758	434	744	+24	−14	576	196
	430.7	667.7			15.3	23.1	4098	9112
	Average reference method values				mean difference		Σx_i^2	

I. 95-percent Confidence Interval

A. SO_2

$$C.I._{95} = \frac{2.306}{9\sqrt{9-1}}\sqrt{9 \times (4098) - (15.3)^2} = 17.342$$

B. NO_x

$$C.I._{95} = \frac{2.306}{9\sqrt{9-1}}\sqrt{9 \times (9112) - (23.1)^2} = 25.857$$

II. Relative Accuracy

A. SO_2

$$\%\ \text{Relative Accuracy} = 100 \times \frac{15.3 + 17.342}{430.7} = 7.579$$

B. NO_x

$$\%\ \text{Relative Accuracy} = 100 \times \frac{23.1 + 25.857}{7.579} = 7.332$$

11.3.7 Instrument Zero Drift and Calibration Drift – 2 Hours and 24 Hours

The instrument 2-hour and 24-hour zero and calibration drifts are evaluated during the 168-hour operational test period. The zero and calibration drift tests examine the analyzer ability to hold its calibration over a period of time. The system drift is evaluated at 2-hour intervals for a total of 15 data sets and at 24-hour intervals for the duration of the operational test period. The system zero and calibration may be adjusted only at 24-hour intervals (or at shorter periods if the manufacturer's written instructions require it).

The zero and calibration drifts are determined by injecting zero and calibration gases for an extractive monitoring system. The 24-hour zero and calibration drift are noted as part of the 24-hour calibration procedure. The 2-hour drift requires 25 data sets. The Federal Register does not require consecutive 2-hour readings to be done on an around-the-clock basis; however, the data for the 2-hour zero and calibration drift should be collected over a maximum of three 24-hour periods. It is recommended that the 15 data sets be collected over the shortest possible time span. The 2-hour checks cannot overlap. All data must be recorded as ppm.

The in-situ or nonextractive monitor may determine the zero and calibration drift by producing a mechanical instrument zero and checking the calibration with a certified calibration gas cell. An alternative is to insert a series of three calibration gas cells into the detector-radiation source path and calculate the zero point from the upscale measurements. A graph must be kept as a record of the procedure used. The zero check using this three-gas-cell method is a special method for cross-stack monitors. It requires a thorough evaluation of the instrument linear response and a careful interpretation of the manufacturer's written instructions. The in-situ instrument calibration may be checked using a certified calibration gas cell equivalent to a 50-percent span concentration. All data are recorded as ppm.

The 2-hour and 24-hour zero and calibration drifts are reported as the sum of the absolute mean value and 95-percent confidence interval as a percent of the instrument span. The difference values (x_i) for the 2-hour zero drift are calculated from the consecutive readings:

$$\begin{pmatrix}\text{Time} \times \\ \text{zero reading} \\ \text{(ppm)}\end{pmatrix} - \begin{pmatrix}\text{Zero reading} \\ \text{2 hours later} \\ \text{after injecting} \\ \text{zero gas}\end{pmatrix} = x_i \quad \begin{matrix}(+ \text{ or } -) \\ \text{(for zero drift)}\end{matrix}$$

The 2-hour calibration drift is corrected for corresponding zero drift. The x_i values are determined by subtracting the change in zero from the change in calibration:

$$\Delta \text{ Span} - \Delta \text{ Zero} = x_i \quad (+ \text{ or } -) \quad \text{(for calibration drift)}$$

The calculations for 2-hour drift are illustrated in the following example:

Instrument Span = 0 - 1000 ppm

Time	Zero Reading	Calibration Reading
X	0 ppm	850 ppm

Time	Zero Reading	Zero Drift Δ Zero (x_i)	Calibration Reading	Δ Span	Calibration Drift Δ Span − Δ Zero (x_i)
X+2 Hours	+6 ppm	+6 ppm	859 ppm	9 ppm	9 − 6 = 3 ppm

This procedure would be carried out for all of the 15 data sets taken during the 2-hour drift test. The x_i values for zero drift and calibration drift are then used in computing the sum of the absolute mean value and 95-percent confidence interval. The individual zero and calibration drift are values then given by:

$$\frac{|\bar{x}| + \text{C.I.}_{95}}{\text{Instrument Span 1000 (ppm)}} \times 100 = \text{Zero drift or Calibration drift}$$

The 24-hour zero and calibration drift x_i values are calculated:

Zero drift

$$\begin{pmatrix}\text{Zero (ppm)}\\ \text{after adjustment}\end{pmatrix} - \begin{pmatrix}\text{Zero (ppm) 24 hours later}\\ \text{after zero gas injection but}\\ \text{prior to zero adjustment}\end{pmatrix} = \underset{\text{(zero drift)}}{x_i}$$

Calibration drift

$$\begin{pmatrix}\text{Calibration (ppm) value}\\ \text{after zero and}\\ \text{calibration adjustment}\end{pmatrix} - \begin{pmatrix}\text{Calibration (ppm) value}\\ \text{24 hours later after}\\ \text{zero adjustment but}\\ \text{prior to calibration adjustment}\end{pmatrix} = \underset{\text{(calibration drift)}}{x_i}$$

The numerical operations are illustrated in the following example:

Instrument Span = 0 - 1000 ppm

DATA FOR 24-HOUR ZERO AND CALIBRATION

Data Set	Time	Zero Reading (ppm)	Calibration Reading (ppm)	Zero Drift (ppm) Δ Zero (x_i)	Calibration Reading (ppm) After Zero Adjustment	Calibration Drift (ppm) Δ Span (x_i)
1	x	0	950	–	–	–
	x+24h	+5	–	+5	959	950 − 959 = −9
2	x_2	0	950	–	–	–
	x_2+24h	−4	–	−4	943	950 − 943 = +7
3	x_3	0	950	–	–	–
	x_3+24h	+6	–	+6	944	950 − 944 = +6
4	x_4	0	950	–	–	–
	x_4+24h	−5	–	−5	948	950 − 948 = +2
5	x_5	0	950	–	–	–
	x_5+24h	−5	–	−5	947	950 − 947 = +3
6	x_6	0	950	–	–	–
	x_6+24h	−5	–	−5	943	950 − 943 = +7
7	x_7	0	950	–	–	–
	x_7+24h	−6	–	−6	945	950 − 945 = +5
				Σx_i −14		Σx_i 21

I. 24-Hour Zero Drift

A. Absolute Mean Value $\bar{x}$

$$|\bar{x}| = \frac{-14}{7} = 2.000$$

B. 95-Percent Confidence Interval

$$C.I._{95} = \frac{2.447}{7\sqrt{7-1}}\sqrt{7\,(188) - (14)^2} = 4.776$$

C. Drift as Percentage of Span (D_s)

$$100 \times \frac{2.000 + 4.776}{1000} = 0.678\%$$

II. The same operations are performed for calibration drift x_i values

A. Absolute Mean Value

$$|\bar{x}| = 3.000$$

B. 95-Percent Confidence Interval

$$C.I._{95} = 5.205$$

C. Drift as Percentage of Span

$$D_s = 0.821\%$$

III. All the above data and operations are also performed for the NO_x monitor.

11.3.8 The Operational Test Period

The SO_2/NO_x continuous monitor must meet all of the specifications given in Performance Specification Test 2. The monitor also must continuously analyze the stack gas pollutant concentration during the 168-hour operational test period. During this time, no corrective maintenance, repairs, replacements, or adjustments may be made to the monitor other than those clearly specified as routine and expected in the manufacturer's written instructions. The operational test period is successfully completed after all of the parameters have been checked with the analyzer operating without corrective maintenance. If the analyzer fails during the operational test period, the specification test must be repeated during another 168-hour test period. It is not necessary to repeat any test that successfully met specifications during the first operational period.

11.4 Performance Specification Test 3 – O_2 or CO_2 Monitors

11.4.1 Introduction

The O_2 or CO_2 analyzer performance requirements are given in Performance Specification Test 3 (PST 3). The monitor response time, calibration, and zero and calibration drifts are evaluated in the operational test period. The regulations have placed increased emphasis on the location of the O_2 or CO_2 monitor when it is used to convert pollutant concentration data to units of the standard. It is important to note restrictions on the placement of CO_2 gas analyzers after limestone scrubbers have been removed (see Federal Register – January 31, 1977).

The performance specification requirements given in the Federal Register for an O_2 or CO_2 monitor are reproduced in Table 11-7.

TABLE 11-7

PERFORMANCE SPECIFICATIONS FOR O_2 OR CO_2 MONITORS

Zero drift (2 hr)*	≤0.4% O_2 or CO_2
Zero drift (24 hr)*	≤0.5% O_2 or CO_2
Calibration drift (2 hr)*	≤0.4% O_2 or CO_2
Calibration drift (24 hr)*	≤0.5% O_2 or CO_2
Operational period	168 hr minimum
Response time	10 min maximum

*Expressed as sum of absolute mean value plus 95-percent confidence interval of a series of tests.

The regulations do not require specific design criteria for O_2 or CO_2. There are a number of different types of analyzers available commercially. The most frequently encountered are paramagnetic or zirconium oxide cells for O_2 analysis and nondispersive infrared instruments for CO_2 analysis.

11.4.2 Monitor Location and Installation

The O_2 or CO_2 monitor must be located and installed at a point that permits measurements of the diluent gas concentration that are directly representative of the total effluent emitted. An O_2 or CO_2 monitor that is used for converting data to units of the standard is to be located at a point where the stack gas is nonstratified, with no air leaking in, or at a position in which gas stratification has been characterized and the sampling interface has been designed to give representative data. A review of the location requirements given for SO_2/NO_x monitors and transmissometers provides details of these requirements.

The O_2 or CO_2 monitor used in converting data to units of the standard must be located at a sampling point where its measurements are representative of the effluent gases sampled by the pollutant monitoring system. This requirement is best fulfilled by installing the O_2 or CO_2 monitor at a location near the SO_2/NO_x monitor such that approximately the same extractive point(s) or in-situ path is sampled for both monitor types. If the pollutant monitor and O_2 or CO_2 monitor are located at different points on the duct, the installation details given in Performance Specification Test 2 must be carefully followed. It is recommended that the sampling locations be verified as representative and equivalent by temperature, velocity, and pollutant traverses of the stack gas. A portable gas monitor used to characterize pollutant concentration at traverse points across the duct in conjunction with temperature and velocity traverses is considered essential for satisfying questions of monitor location.

11.4.3 O_2 or CO_2 Monitor Calibration Gases

The Federal Register states that known concentrations of O_2 or CO_2 corresponding to 50 percent and 90 percent of instrument span (as given in the subparts of the CFR for each affected facility) be used to calibrate the instrument. The manufacturer's instructions should be followed for the type of inert carrier gas required for the O_2 or CO_2 and instrument zero gas. If the O_2 analyzer span range is greater than 21 percent O_2, ambient air may be used as the calibration gas. The calibration gas mixtures must be analyzed by triplicate-reference-method 3 tests no more than 2 weeks prior to use in the specification test.

11.4.4 Instrument Calibration Check

The wide variation in analyzer designs may make procedures for this test and the following tests of instrument response and drift inapplicable. The EPA Administrator must approve any alternative procedures employed for the tests.

The calibration of the instrument is checked by establishing a calibration curve. Zero, mid-range, and 90-percent span gases are injected into the analyzer. The data are plotted as instrument response versus gas value. The graph must be consistent with the expected response curve described by the manufacturer or additional measurements must be made to verify the instrument accuracy. This test should be performed with the analyzer installed as intended for use in the field.

The O_2 or CO_2 analyzer is operated for a 168-hour conditioning period after the calibration check. The monitor may be maintained and repaired as needed to prepare it for the 168-hour operational test period. During the operational test period, the monitor must continuously monitor the stack gas without corrective maintenance or repair. Manufacturer's written instructions for routine procedures are permitted. Any other type of repair or corrective maintenance required by the analyzer will cause the operational test period to end. The operational test period must then be repeated. Performance specifications successfully completed during the first operational test period do not require repetition.

11.4.5 Response-Time Test

The response-time test is performed during the 168-hour operational test period with the monitor installed as intended for use at the affected facility. The entire sampling interface is included in the test with careful attention made to assure that system flowrates, line diameters, pumping rates, and pressures are the same as in normal operating procedure. The test for response time must be repeated for each sampling point – if the analyzer is used to sample more than one source, the response time must be determined for each system.

The system response time is determined by injecting zero gas into the sampling interface (or as close as possible) to establish a stable output reading. A known concentration of calibration gas at 90 percent of span is quickly switched into the system. The time required for the instrument to reach 95 percent of the final stable response is recorded. The system is allowed to stabilize at the upper span reading, then zero gas is reinjected into the sampling interface. The time needed for the instrument to reach 95 percent of the final stable zero is recorded. The procedure is carried out for three sets of upscale-downscale tests. A nonextractive system is evaluated by switching the highest available calibration gas concentration into and out of the sample path and by recording the 95-percent upscale and downscale response times.

The system response time is calculated from the time intervals required for 95 percent of final stable response. The mean of the three upscale response times is found by:

$$\sum \frac{\text{upscale response}}{3} = \text{mean upscale response time}$$

and the mean of the three downscale times is calculated:

$$\sum \frac{\text{downscale response}}{3} = \text{mean downscale response time}$$

The upscale-downscale response should not deviate more than 15 percent of the slower time:

$$100 \times \frac{\text{(mean upscale response time) - (mean downscale response time)}}{\text{slower time}} \leqslant 15\%$$

The system response time is reported as the slower time.

11.4.6 Zero and Calibration Drifts – 2-hour and 24-hour

The 2-hour and 24-hour zero and calibration drift tests are performed for the O_2 and CO_2 monitor in the same manner as for the SO_2/NO_x analyzer. The 2-hour drifts are determined from 15 sets of zero and calibration readings taken at 2-hour intervals. (Readings need not be consecutive but must not overlap.) Zero gas is introduced into the system and analyzer zero output is recorded. The change in readings between consecutive 2-hour measurements is the x_i values for zero drift calculations:

$$\Delta \text{ Zero} = \text{[Time x zero reading (ppm)]} - \text{[Time x + 2-hr zero reading (ppm)]} = x_i \text{ (+ or −)}$$

The calibration drift x_i values are determined by injecting mid-range calibration gas (for nonextractive monitors a calibration gas cell functionally equivalent to 50 percent of span is used) at 2-hour intervals and correcting the calibration drift values for corresponding zero drift:

$$\Delta \text{ Span} = \text{[Time x calibration reading (ppm)]} - \text{[Time x + 2-hr calibration reading (ppm)]}$$

$$\Delta \text{ Span} - \Delta \text{ Zero} = x_i \text{ (+ or -) for calibration drift}$$

The respective x_i values for zero and calibration drifts then are used to calculate separately the absolute mean difference and 95-percent confidence interval for the individual drifts. The 2-hour zero drift or calibration drift is then expressed as the sum of the respective absolute mean difference and 95-percent confidence interval:

$$|\bar{x}| + \text{C.I.}_{95} = \text{zero or calibration drift}$$

The 24-hour zero and calibration drifts are determined by taking the difference between instrument setting at calibration and the values 24 hours later.

24-hour zero drift

$$\left(\begin{array}{c} \text{zero setting} \\ \text{after adjustment} \\ \text{(ppm)} \end{array} \right) - \left(\begin{array}{c} \text{zero setting 24 hours} \\ \text{later before adjustment} \\ \text{(ppm)} \end{array} \right) = \text{difference } (x_i)$$

24-hour calibration drift

$$\left(\begin{array}{c}\text{calibration}\\ \text{setting after}\\ \text{adjustment (ppm)}\end{array}\right) - \left(\begin{array}{c}\text{calibration concentration}\\ \text{24 hours later after zero}\\ \text{adjustment but before}\\ \text{calibration adjustment}\end{array}\right) = \text{difference } (x_i)$$

The sum of the absolute mean value and 95-percent confidence interval is then expressed as the respective zero or calibration drift:

$$|\bar{x}| + C.I._{95} = \text{24-hour zero or calibration drift}$$

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CHAPTER 12

QUALITY ASSURANCE

12.1 Introduction

A continuous monitoring system will provide valid, reliable data when properly maintained and operated. The investment involved in purchasing a continuous monitoring system is only the first step in supplying emissions data from a source. The system must be maintained at regular intervals to ensure that it is operating within prescribed limits. A monitoring system that is not well maintained becomes a possible legal liability and is not cost effective for the user. It is in the interest of both the user and the regulatory agency to have the monitoring system provide good data on source emissions. This is required by the Federal regulations; however, a user benefits from the data by avoiding legal conflicts, protecting its monitoring investment, in addition to gaining a reliable process control monitor.

The continuous monitors presently available on the commercial market will supply valid data when an organized program of routine maintenance and quality assurance is carried on. All monitors will need some maintenance. If the maintenance program is organized following manufacturer's instructions at the time of installation, then reasonably followed throughout the operational life of the analyzer, the monitor will provide useful emissions information. A system of routine maintenance will prove much less costly or bothersome than a neglected system that frequently breaks down. The legal problems and repair headaches that follow using a poorly maintained system soon become much more trouble than originally employing a good maintenance program. The following paragraphs deal with quality assurance procedures for keeping a continuous monitor in good operating condition.

12.2 Calibration Gas Evaluation

The continuous monitoring system will yield valid data only after it has been properly calibrated. An analyzer delivers an output signal proportioned to the pollutant concentration in analysis. The actual concentration is obtained by calibrating the instrument against a known concentration of pollutant. The significance of the instrument calibration for obtaining data on pollutant emissions is obvious. The calibration of an analyzer is performed with gases purchased from commercial suppliers.

A commercial calibration gas manufacturer product must always be checked to ensure that the stated gas concentration in the cylinder is accurate. The gas concentration marked on a cylinder should never be assumed to be correct. The cylinder concentration must be checked using the reference method gas analysis, which is required for the Performance Specification Test procedures. The regulation subparts must be read carefully to determine the required calibration gas for an affected facility. This must correlate with the requirement stated by the instrument manufacturer. The gas is then analyzed no more than 2 weeks prior to use in the Performance Specification Test by the applicable reference method. A check also is required at 6-month intervals by a reference method test. The regulations allow the cylinder to be checked at less frequent intervals if the shelf life is guaranteed by the manufacturer to exceed a 6-month stability. It is recommended, however, that all gases be analyzed every 6 months.

As mentioned earlier, EPA is developing a protocol for the use of National Bureau of Standards (NBS) and NBS traceable gases and forgoing the reference method analyses. A comment to this effect is made in 40 FR 46251 October 6, 1975; however, it has not yet been incorporated into the body of the regulations.

Reference methods 3, 6, and 7 describe wet chemical analysis of carbon dioxide, oxygen, sulfur dioxide, and oxides of nitrogen. These methods have shown good results when properly performed. The details of the procedures are given in the August 18, 1977, Federal Register. It is good practice to cross check new cylinders by using them in the analyzer calibrated with the existing gases. The data from the already analyzed calibration gases, new cylinder gases, and reference methods then may be correlated. This provides a thorough check of all gases and may indicate problems not previously anticipated.

The calibration gases must be checked by the reference methods even if they are traceable to NBS reference gases. The term traceable to NBS is not an absolute assurance of accuracy. It can have several meanings. The gas manufacturer may be able to trace all its gases to NBS by calibrating a bulk gas against an NBS cylinder. This is a general procedure involving much less expense than checking every cylinder shipped against an NBS gas. There could conceivably be some problems in diluting and filling cylinders from this bulk gas, yet it would be traceable to a reference standard. The real reference standard is the original NBS cylinder, which must be carefully stored and used before deterioration. It should be clear that all calibration gases should be checked by reference method gas analysis to assure that the cylinder concentration is correct and has not changed by reaction in the cylinders. Finally, no cylinder may be expected to give good results if the interior pressure is less than or equal to 100 psi. If the cylinder pressure is low, change it before problems arise.

12.3 Instrument Performance Evaluation

A complete Performance Specification Test is a complex, expensive undertaking. It is used to fully evaluate system operation to within given limits in the Federal regulations. The evaluation of a continuous monitoring system after the initial Performance Specification Test need not involve repetition of the tests. The plant owner or operator of an affected facility should make efforts for proper maintenance of the continuous monitoring system. It has been possible for regulatory agencies to adopt a three-level form of monitoring inspection procedures. The user and the agency would benefit; the user would receive guidance and comment on system up-keep and maintenance; the agency would be able to perform its duties efficiently with less direct enforcement proceedings.

12.4 EPA Inspection Procedures

12.4.1 Level-One Inspections – (Office Evaluation of Quarterly Reports)

A level-one inspection is intended to identify problem areas. The agency inspector would carry out routine evaluation of a plant's quarterly emissions report. The inspector would check:

- Reports of periods and magnitudes of excess emissions
- Nature and cause of each period of excess emissions
- Periods during which continuous monitoring system was inoperative
- Record of calibration checks, adjustments, and maintenance performed on the monitoring system.

These administrative evaluations save agency manpower and expense. Problem areas in the monitoring system and reports should present themselves upon thorough evaluation of the above items. The agency then can contact the plant operator to assist in checking out the monitoring system, possibly avoiding a situation calling for more extensive agency action. This could be considered an exchange of information rather than an adversary confrontation.

The quarterly reports probably will not be very lengthy, yet the experienced inspector can gain insights into the operation of the continuous monitoring system. The calibration procedures and routine maintenance indicated for the analyzer can suggest to the knowledgeable inspector whether the instrument is well cared for. The emissions records should illustrate the normal operating parameters of the plant and its control equipment. If the records show frequent excess emissions, the plant may have a faulty monitor or control systems; data that are important to the plant and the agency. The calculation methods may indicate operator understanding of the regulations. The experienced agency inspector then may be able to decide upon the necessity of helping plant operators to understand the intent of the regulations and necessary calculations fully. The quarterly report is a good indicator of compliance when in the hands of a trained inspector.

12.4.2 Level-Two Inspection – (Field Inspection)

The level-two inspection procedures are initiated when the quarterly report has given indications that the inspection is warranted. The inspector may feel that the quarterly report or other indicators require a site inspection of the affected facility. The operations of the plant process and its monitor system may need review to satisfy the inspector that all regulations are being properly carried out. The inspector is required to do this type of inspection to protect the plant and the environment.

A second-level continuous monitor inspection includes an examination of all major parts of the monitoring program. The inspector should check instrument zero and calibration procedures, determining the proper methods of instrument operation from the manufacturer's written instructions. The plant operator should explain the instrument maintenance log to the inspector, in addition to routine system maintenance procedures. The strip-chart or data-logging recorder is checked to ensure that a good record is being made of the instrument output. The storage and retrieval system for these records should be reviewed for reliability and accuracy. The inspector then will want to review data conversion and emission calculations methods with the plant operator.

The specific areas a level-two inspector would be examining are outlined in the check list presented in Table 12-1. This list will aid in determining the efficiency and proper operation of the monitoring system. It may be used in decisions concerning the step to a level-three inspection.

TABLE 12-1

LEVEL-TWO INSPECTION CHECK LIST

				Needs Revision	
	Yes	No	N/A	Yes	No
I. Monitor Zero and Calibration Time Needed					
A. Performed every 24 hours					
B. Performed by experienced personnel					
C. Procedure follows manufacturer written instructions					
D. Calibration gases analyzed within last 6 months					
1. Tank pressure above 100 psi					
2. Calibration checks entire sampling interface					
E. Data log kept					
1. Each entry dated and signed					
2. Neat, orderly appearance					
3. Up-to-date					
4. Maintenance record included					
5. Manufacturer recommended maintenance followed					
6. Unusual trends in instrument performance evident					
7. Inoperative Monitor time recorded					
a. Source of problem recorded					
b. Corrective procedure given					
c. Problem repetitive					

TABLE 12-1

LEVEL-TWO INSPECTION CHECK LIST—Continued

				Needs Revision	
	Yes	N	N/A	Yes	No
F. General inspector comment on procedures					
1. Acceptable and effective					
2. Could be improved					
3. Inadequate					
II. Maintenance Procedures Outlined for All Plant Personnel Involved in Monitor Program					
III. Data Recording System					
A.. Type					
1. Strip-chart recorder					
2. Data-logging system					
B. Electronic interface					
1. Instrument output checked					
a. Output signal at zero					
b. Output signal at span					
C. Strip-chart record clear					
1. Zero offset 10% at recorder					
2. Pollutant concentration readily identified					
3. Inking system in good order					
4. Plenty of spare charts and pens					
5. All pertinent chart data (date, speed, instrument settings, etc.)					
6. Charts easily identified for record retrieval					
7. Chart shows cyclic nature of process					
8. Chart indicates problem exists in monitoring system					
IV. Data Handling and Calculation					
A. All monitor data recorded					
1. Any data discarded					
2. Any data omitted in averaging monitor readings					
B. Data conversion to units of the standard					
1. O_2 F-factor; wet or dry					
2. CO_2 F-factor; wet or dry					

TABLE 12-1

LEVEL-TWO INSPECTION CHECK LIST—Continued

				Needs Revision	
	Yes	No	N/A	Yes	No
3. F-factor determined by chart					
4. F-factor determined by fuel analysis					
5. F-factor determined for each batch of fuel					
6. Operator maintains record of fuel batch combusted					
C. Excess emissions recorded in units of standard					
1. Frequent excess emissions					
2. Frequent plant breakdowns					
D. Calculations					
1. Conversion factors correctly derived					
2. Equations and methods clear					
3. Any noticeable errors					
V. General Check Points					
A. System seems to operate well					
B. Plant maintenance seems appropriate					
C. Instrument drift appears normal					
D. Records procedures adequate					
E. Calibration materials and instrument spare parts easily available					
F. Instrument site properly located for representative readings					
G. Instrument easily accessible					

12.4.3 Level-Three Inspection

The level-three inspection procedures involve a complete evaluation of the source continuous monitoring system. The level-three inspection becomes necessary after level-two procedures have indicated unsatisfactory monitoring performance at the source. The inspector may feel that performance of the entire monitoring program can be assessed only by direct comparison with agency results obtained by an experienced sampling team. The sampling team would perform manual reference method testing, a possible portable instrumental gas analysis, or a process operation inspection. The results from these tests then would be correlated to previous source monitoring data. The level-three inspection includes a thorough evaluation of the monitoring system. A Performance Specification Test would be performed with agency inspectors observing all procedures.

The results of a level-three inspection may determine the necessity of legal action against the plant operator if the regulations are not being followed. The level-three inspection is performed when other inspections indicate significant problems in the system. When legal action may be necessary, a level-three inspection need not be viewed as the first step in such a proceeding until all results have been carefully examined.

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APPENDIX A

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APPENDIX B

CALCULATIONS FOR THE PERFORMANCE SPECIFICATION TEST

A. Calculations

The "Confidence Interval for the Mean Estimated Value" is what is calculated in the Performance Specification Test. For example, the requirement that an SO_2 monitor have a 2 hr zero drift of 2 percent of span means that the computed "Confidence Interval for the Mean Estimated Value" divided by the instrument span value be $\leqslant 2$ percent.

One calculates the performance parameter (PP) by using the formula

$$PP = \frac{|\overline{x}| + |CI_{95}|}{RV} \times 100$$

where:

$|\overline{x}|$ = the absolute mean value $|\overline{x}| = \frac{1}{n} \sum_{i=1}^{n} (A_i - W_i)$

A_i = analyzer data – 2-hr or 24-hr period

W_i = concurrent wet chemistry data – 2-hr or 24-hr period

where:

CI_{95} = the two-sided 95-percent confidence interval estimate of the average mean value

$$CI_{95} = \frac{t_{0.975}}{n\sqrt{n-1}} \sqrt{n\,(\Sigma x_i^2) - (\Sigma x_i)^2}$$

where:

$x_i \quad = A_i - W_i$

$t_{0.975}$ = The t value derived in the t test corresponding to the probability that a measured value will be within 95 percent of true value.

(Note: $t_{0.975} = t_{1-\alpha/2} = t_{1-.05/2} = t_{0.975}$)*

The values of $t_{0.975}$ are obtained from Table B-1.

TABLE B-1

VALUES FOR $t_{0.975}$

n	$t_{0.975}$	n	$t_{0.975}$
2	12.706	10	2.262
3	4.303	11	2.262
4	3.182	12	2.201
5	2.776	13	2.179
6	2.571	14	2.160
7	2.447	15	2.145
8	2.365	16	2.131
9	2.306		

RV is either a reference value, a calibration value, or a span value. In the case of opacity monitors, values of RV are *not* divided into $|\bar{x}| + |CI_{95}|$ to obtain PP.

This is all that is needed in the calculation of the performance parameters. The major problem in doing the calculations results from misunderstanding the fact that the absolute mean value, $|\bar{x}|$, and the absolute value of the confidence interval $|CI_{95}|$ must be added together.

It should be noted, that since $|CI_{95}|$ must be added to $|\bar{x}|$ to obtain PP, an increase of the number of samples will decrease the contribution of CI_{95} to PP. This is due to the fact that n is in the denominator of CI_{95} and that $t_{0.975}$ decreases with n.

*This means that for a 5-percent level of significance, there is a 2-1/2-percent probability of obtaining t greater than that in Table B-1 and a 2-1/2-percent probability of obtaining t smaller than the negative of the tabulate value.

Also, for low values of calibration or span gases, PP values may be correspondingly higher. Also in the case of a source with low emission values for SO_2, the PP for accuracy of an SO_2 monitor would be higher than if the same monitor were placed at a source emitting higher concentrations of SO_2.

B. Rationale Behind the Confidence Interval Calculation

The use of the t test and the confidence interval calculation in obtaining performance parameters is an attempt to place a numerical value on the correlation between two parameters, e.g., the SO_2 value given by the instrument and the SO_2 value determined by the manual reference method. If the values correlate well, the value of t will be low, i.e., both the monitor and the reference method would each be measuring the same thing, each measuring it relatively accurately.

Essentially, this statistical method arises out of regression analysis. Say, for example, the monitor gives a value X and the reference method gives a value Y. A least squares regression method attempts to show that there exists a relationship such as

$$Y = A + BX$$

where A and B are numbers.

In Figure B-1(a) the parameter X and Y would be highly correlated; in Figure B-1(b) the parameters would be independent. What the t values (or t test) then give us, is the value of t that one would obtain if there was a 95-percent probability that X and Y correlated. This is the 95-percent confidence level.

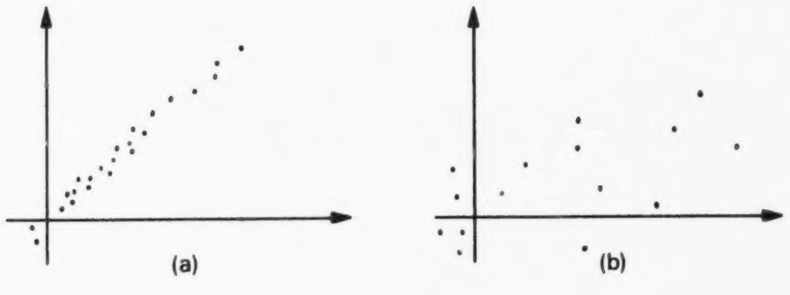

FIGURE B-1

The confidence interval for the "mean estimated value of a number" is given by

$$CI_{mean} = |\bar{x}| + tS$$

where $|\bar{x}|$ is the mean estimated value. S is the standard deviation of the mean. Here, t is obtained from the table and S is computed. Therefore,

$$
\begin{aligned}
CI_{mean} &= |\bar{x}| + t\,\frac{1}{n}\sqrt{\frac{\Sigma(x_i)^2 - (\Sigma x_i)^2}{n\,(n-1)}} \\
&= |\bar{x}| + \frac{t}{n\sqrt{n-1}}\sqrt{n\,(\Sigma x_i^2) - (\Sigma x_i)^2} \\
&= |\bar{x}| + |CI_{95}|
\end{aligned}
$$

and

$$PP = \frac{CI_{mean}}{RV} \times 100$$

APPENDIX C

F-FACTORS

The New Source Performance Standards require that emissions from an affected facility be reported to the Administrator in terms of process rate. A process rate standard is written in units that relate pollutant emissions to the production rate of the industry:

$$\frac{\text{pollutant emission weight}}{\text{process production rate}}$$

The emission rate (E) is given in units such as:

- pounds/million Btu
- grams/million calories
- pounds/ton

The F-factor is used to calculate the emission rate in the units of the standard. It reduces the amount of data necessary to complete the emission rate calculation. The relationships that make possible emission rate calculation using an F-factor are explained in this section. A table of F-factors and summary to types of F-factors is included for easy reference.

> *Definition:* The F-factor for making emission rate calculations is developed from a chemical and combustion analysis of the fuel burned to operate a production process. The F-factor is the ratio of the theoretical volume of dry gases (V_t) given off by complete combustion of a known amount of fuel, to the gross caloric value of the burned fuel (GCV).

$$F_d = \frac{\text{volume dry combustion gases}}{\text{gross calorific value}} = \frac{V_t}{GCV}$$

The values of the constituents in the F-factor are determined by a fuel analysis. There are two types of fuel analysis, proximate and ultimate analysis.

Proximate analysis — a fuel analysis procedure that expresses the principal characteristics of the fuel as:

1. Percent moisture
2. Percent ash
3. Percent volatile matter
4. Percent fixed carbon
5. Percent sulfur
6. Heating value (Btu/lb)*
7. Ash fusion temperature

(Total 1–5 = 100 percent)

*Gross Caloric Value (GCV) — Also termed the "high heating value." The total heat obtained from the complete combustion of a fuel referenced to a set of standard conditions. The GCV is obtained in the proximate analysis as the "heating value."

Ultimate analysis – the determination of the exact chemical composition of the fuel without paying attention to the physical form in which the compounds appear. The analysis is generally given in terms of percent hydrogen, percent carbon, percent sulfur, percent nitrogen, and percent oxygen.

The data generated in an ultimate analysis of a given fuel allow the calculation of an F_d factor based on the composition of the fuel constituents. The individual chemical components are included in the theoretical volume as uncombined elements. Each contributes to the total V_t based upon the percentage present in the fuel. An F-factor can then be calculated for any fuel when the percent composition of each constituent is known:

$$F_d = \frac{227.0(\%H) + 95.7(\%C) + 35.4(\%S) + 8.6(\%N) - 28.5(\%O)}{GCV} \quad \text{metric units}$$

$$F_d = 10^6 \frac{6.34(\%H) + 1.53(\%C) + 0.57(\%S) + 0.14(\%N) - 0.46(\%O)}{GCV} \quad \text{English units}$$

The F-factor is developed from theoretical calculations on the combustion of a fuel. The preceding equations account for only a stoichiometric amount of oxygen – enough oxygen to completely oxidize the fuel to its combustion products. An industrial facility burning large quantities of fuel adds a stoichiometric amount of air (oxygen and nitrogen) and some excess air to assure complete combustion of fuel. The volume of the combustion products is related to the heat input of the fuel and the excess air in the expression:

$$\frac{Q_s}{Q_H} \times \left[\begin{array}{c}\text{Excess} \\ \text{Air Correction} \\ \text{Term}\end{array}\right]$$

where:

Q_s = volumetric flowrate of dry combustion gas

Q_H = heat input rate

The stoichiometric oxygen present would be consumed for combustion of the fuel. The remaining oxygen present in the combustion gases is, therefore, an excess. The percentage excess is then calculated using the percent oxygen in air and the percent oxygen found in the combustion gases:

$$\text{Percent excess air} = \frac{20.9 - \%O_2}{20.9} \quad \text{(dry basis)}$$

It is then possible to show that combustion gases at an actual combustion facility can be corrected to the theoretical combustion gas volume:

$$\frac{Q_s}{Q_H} \times \frac{20.9 - \%O_2}{20.9} = \frac{V_t}{GCV}$$

which is dimensionally consistent if we consider Q_H in terms of heat input per pound of fuel per hour:

$$\frac{Q_s}{Q_H} \times \frac{20.9 - \%O_2}{20.9} = \frac{V_t}{GCV}$$

$$\frac{\frac{DSCF_{(s)}}{Hr}}{10^6\ Btu/lb} \times \frac{20.9 - \%O_2}{20.9} = \frac{DSCF_{(t)}}{10^6\ Btu/lb}$$

$$\frac{DSCF_{(s)}}{10^6\ Btu/lb} = \frac{DSCF_{(t)}}{10^6\ Btu/lb}$$

The importance of the F-factor becomes obvious if we now write the equations:

$$\frac{Q_s}{Q_H} = \frac{V_t}{GCV} \times \frac{20.9}{20.9 - \%O_2} = F\ \frac{20.9}{20.9 - \%O_2}$$

which illustrates that by using the F_d-factor generated in the laboratory for a given fuel and correcting for percent excess air in the combustion gases, it would not be necessary to determine the stack gas volumetric flowrate or the fuel feed rate of a combustion source. The emission rate could then be calculated from the pollutant concentration in the stack gas, F-factor, and the percent excess air.

$$E = \frac{C_s Q_s}{Q_H}$$

$$E = C_s F_d\ \frac{20.9}{20.9 - \%O_2}$$

$$E = \frac{lb}{DSCF_{(s)}}\ \frac{DSCF_{(t)}}{10^6\ Btu} \left[\frac{20.9}{20.9 - \%O_2}\right] = \frac{lb}{10^6\ Btu}$$

The F_d-factor may be used for emission rate calculations if the percent oxygen ($\%O_{2ws}$) and the pollutant concentration (C_{ws}) are determined on a wet basis and if the moisture content (B_{ws}) of the stack gas is known. The emission rate is then corrected to a dry basis for reporting to the Administrator by the equation:

$$E = C_{ws}\ F_d\ \frac{20.9}{20.9\ (1 - B_{ws}) - \%O_{2_{ws}}}$$

Different Types of F-Factors

The F_d-factor is derived for dry gas volumes and determining excess air by measuring percent oxygen in the flue gas on a dry basis. There are other F-factors which have been developed for measurements on a wet basis or for excess air determinations made by measuring percent carbon dioxide in the flue gas.

F_c: Carbon Dioxide F-Factor

$$F_c = \frac{20.0(\%C)}{GCV} \quad \text{(metric units)}$$

$$F_c = \frac{321 \times 10^3 (\%C)}{GCV} \quad \text{(English units)}$$

$$E = C_s F_c \frac{100}{\%CO_2}$$

F_w: Wet F-Factor

$$F_w = \frac{347.4(\%H) + 95.7(\%C) + 35.4(\%S) + 8.6(\%N) - 28.5(\%O) + 13.4(\%H_2O)}{GCV} \quad \text{(metric units)}$$

$$F_w = \frac{10^6 \left[5.56(\%H) + 1.53(\%C) + 0.57(\%S) + 0.14(\%N) - 0.46(\%O) + 0.21(\%H_2O)\right]}{GCV} \quad \text{(English units)}$$

The wet F-factor, F_w, may be used in the expression:

$$E = C_{ws} F_w \frac{20.9}{20.9\ (1 - B_{wa}) - \%O2_w}$$

where:

C_{ws} = the concentration of the pollutant given on a wet basis

$\%O2_w$ = the percent oxygen on a wet basis

B_{wa} = the ambient air moisture fraction

B_{wa} may be determined by a number of methods given in 41 FR 44838 October 12, 1976. This method may be used in systems which measure gas concentrations on a wet basis, such as the Lear Siegler and DuPont systems. For wet scrubber applications, a determination of B_{ws} must be made, then utilized in the expression given on the previous page.

F-Factor for Combination Fuels

A source may utilize a combination of fossil fuels. The F-factor for a combination of fuels is determined from the general expression:

$$F_m = \sum_{i=1}^{n} X_i F_i$$

where:

F_m = F-factor for the fuel mixture (gaseous, solid, liquid fuel)

X_i = fraction of total heat input from each type fuel

F_i = the applicable F-factor for each fuel in the mixture

which states that the F-factor for the mixture is the sum of the products of the fraction of heat input for each fuel multiplied by the applicable F-factor for that fuel. All F-factors must be on a consistent basis – O_2 or CO_2; wet or dry. The example shows the calculations.

A combustion source burned the following combination of fuels to produce process steam:

Fraction Heat Input	Fuel Type	F_d DSCF/10^6 Btu	F_c SCF/10^6 Btu
10%	Natural gas	8740	1040
10%	Butane	8740	1260
20%	Oil	9220	1430
60%	Bituminous Coal	9820	1810

The combination F_d-factor is:

$$F_d = F_m = (0.10)(8740) + (0.10)(8740) + (0.20)(9220) + (0.60)(9820) = 9484 \frac{\text{DSCF}}{10^6 \text{ Btu}}$$

The combination F_c-factor is:

$$F_c = F_m = (0.10)(1040) + (0.10)(1260) + (0.20)(1430) + (0.60)(1810) = 1602 \frac{\text{SCF}}{10^6 \text{ Btu}}$$

The plant engineer may obtain the F-factor values used in calculating the combination F-factor from Table C-1. These values have been determined for various categories of fuel from fuel analysis data taken of a large number of samples. The F_d-factors for a fuel category have shown that they may be calculated to within ±3 deviation; the F_c-factors have been calculated to be within ±5.9 percent deviation. The Federal Register gives the engineer the option to use these factor values, or with approval from the Administrator, to develop F-factors from fuel analysis for the fuel as received at the plant.

Compilation of F-Factors and Emission Rate Calculations

Tables C-1, C-2, and C-3 give a summary of F-factors, units, and emission rate calculations. The subscript w indicates a wet basis expression; all others are on a dry basis.

TABLE C-1

F-FACTOR CALCULATION EQUATIONS

$$F_d = \frac{227.0\%H + 95.7\%C + 35.4\%S + 8.6\%N - 28.5\%O]}{GCV} \qquad \text{(metric units)}$$

$$F_d = \frac{10^6\,[3.64\%H + 1.53\%C + 0.57\%S + 0.14\%N - 0.46\%O]}{GCV} \qquad \text{(English units)}$$

$$F_c = \frac{20.0\%C}{GCV} \qquad \text{(metric units)}$$

$$F_c = \frac{321 \times 10^3\%C}{GCV} \qquad \text{(English units)}$$

$$F_w = \frac{347.4\%H + 95.7\%C + 35.4\%S + 8.6\%N - 28.5\%O + 13.4\%H_2O^*}{GCV_w} \qquad \text{(metric)}$$

$$F_w = \frac{10^6\,[5.56\%H + 1.53\%C + 0.57\%S + 0.14\%N - 0.46\%O_2 + 0.21\%H_2O^*]}{GCV_w} \qquad \text{(English)}$$

$$F_w = \sum_{i=1}^{n} X_i F_i \ \text{(consistent basis)}$$

*Note: The $\%H_2O$ term may be omitted if %H and %O include the unavailable hydrogen and oxygen in the form of H_2O.

TABLE C-2

F-FACTORS FOR VARIOUS FUELS [a,b]

Fuel Type	F_d $\frac{\text{DSCF}}{10^6\ \text{Btu}}$	F_w $\frac{\text{WSCF}}{10^6\ \text{Btu}}$	F_c $\frac{\text{SCF}}{10^6\ \text{Btu}}$	F_o
Coal				
Anthracite	10140 (2.0)	10580 (1.5)	1980 (4.1)	1.070 (2.9)
Bituminous	9820 (3.1)	10680 (2.7)	1810 (5.9)	1.140 (4.5)
Lignite	9900 (2.2)	12000 (3.8)	1920 (4.6)	1.0761 (2.8)
Oil	9220 (3.0)	10360 (3.5)	1430 (5.1)	1.3461 (4.1)
Gas				
Natural	8740 (2.2)	10650 (0.8)	1040 (3.9)	1.79 (2.9)
Propane	8740 (2.2)	10240 (0.4)	1200 (1.0)*	1.10 (1.2)*
Butane	8740 (2.2)	10430 (0.7)	1260 (1.0)	1.479 (0.9)
Wood	9280 (1.9)*	–	1840 (5.0)	1.5 (3.4)
Wood Bark	9640 (4.1)	–	1860 (3.6)	1.056 (3.9)

[a] Numbers in parentheses are maximum deviations (%) from the midpoint F-factors.

[b] To convert to metric system, multiply the above values by 1.123×10^{-4} to obtain scm/10^6 cal.

Note: All numbers below the asterisk (*) in each column are midpoint values. All others are averages.

TABLE C-3

F-FACTORS AND EMISSION RATE CALCULATION

Factor	Units	Measurement Required For Excess Air Determination	Calculations	Comments
F_d	$\frac{DSCF}{10^6\ Btu}$	%O (dry basis)	$E = C_s F_d \frac{20.9}{20.9 - \%O_2}$	C_s determined on dry basis
F_c	$\frac{DSCF}{10^6\ Btu}$	$\%CO_2$ (dry or wet basis)	$E = C_s F_c \frac{100}{\%CO_2}$	C_s on dry or wet basis consistent with CO_2 measurement
F_w*	$\frac{WSCF}{10^6\ Btu}$	$\%O_2$ (wet basis)	$E = C_{ws} F_w \frac{20.9}{20.9(1 - B_{wa}) - \%O_2}$	The "wet" F-factor, C_{ws} and $\%O_2$ on wet basis B_{wa} = average moisture content of ambient air
F_d	$\frac{DSCF}{10^6\ Btu}$	$\%O_2$ (wet basis)	$E = C_{ws} F_d \frac{20.9}{20.9(1 - B_{ws}) - \%O_2}$	F_d used to calculate E with $\%O_2$ and C_{ws} on a wet basis and gas moisture content known
F_o	----	----	$F_o = \frac{20.9}{100}\frac{F_d}{F_c} = \frac{20.9 - \%O_2}{\%CO_2}$	Miscellaneous factor useful for checking Orsat data

*Note: The wet F-factor, F_w, may not be used in any application which involves the addition or removal of moisture from the combustion effluent. As a result, it is not suitable for wet scrubber applications without additional correction.

Note also: B_{wa} = Amount of moisture in ambient air, which value can be established by any of the following four methods.

a) Fixed constant value of 0.027 allowed
b) Continuous measured value
c) Monthly value based on previous history
d) Annual value based on previous history

Sulfuric Acid Conversion Factor

A sulfuric acid manufacturing operation must establish a conversion factor for converting continuous monitoring data to units of the standard (Kg/metric ton, lb/short ton). The factor must be determined a minimum of three times per day by measuring the sulfur dioxide concentration entering the gas conversion unit. The Reich test is generally used for measuring SO_2 at the plant. The conversion factor is calculated:

$$CF = K \frac{1.000 - 9.015\,(r)}{r - s}$$

where:

CF = conversion factor (kg/metric ton per ppm, lb/short ton per ppm).

K = constant derived from material balance. For determining CF in metric units, K = 0.0653. For determining CF in English units, K = 0.1306.

r = percentage of sulfur dioxide by volume entering the gas converter. Appropriate corrections must be made for air injection plants subject to the Administrator's approval.

s = percentage of sulfur dioxide by volume in the emissions to the atmosphere determined by the continuous monitoring system.

The continuous monitoring data are then multiplied by the conversion factor to give units in the standard:

$$\text{monitor ppm} \times \frac{\text{Kg/metric ton}}{\text{ppm}} = \text{Kg/metric ton} \ \text{(metric units)}$$

Nitric Acid Conversion Factor

A nitric acid manufacturing operation must establish a conversion factor for converting continuous monitoring data to units of the Applicable Standard (kg/metric ton, lb/short ton). The conversion factor must be established by measuring plant emissions in terms of NO_2 concurrent with reference method tests of the emissions. The conversion factor is determined from monitor data taken only during the reference method test. It is calculated by dividing the average reference method NO_2 data by the NO_2 data average measured by the monitor. The ratio is expressed in units of the standard:

$$\begin{matrix}\text{Average}\\ \text{Reference Method}\end{matrix}\ \text{gm/m}^3 \times 0.602 = \text{Kg/ton (metric units)}$$

$$CF = \frac{\text{Reference Method Kg/ton}}{\text{Monitor ppm}} = \text{Kg/ton/ppm}$$

The conversion factor multiplied by monitor concentration data then yields units of the standard:

$$\frac{\text{monitor}}{\text{ppm}} \times \text{Kg/ton/ppm} = \text{Kg/ton}$$

Other Uses of F-Factors

If values for Q_s, the stack gas volumetric flowrate, and Q_H, the heat input rate, are obtained, as they often are, several cross-checks can be made by comparing various calculated F-factor values with the tabulated values.

Equations that can be used to do this are given below:

$$F_d \text{ (calc)} = \frac{Q_s}{Q_H} \frac{(20.9 - \%O_2)}{20.9}$$

$$F_w \text{ (calc)} = \frac{Q_{sw}}{Q_H} \frac{20.9\,(1 - B_{wa}) - \%O_{2_w}}{20.9}$$

$$F_c \text{ (calc)} = \frac{Q_s}{Q_H} \frac{\%CO}{100} = \frac{Q_{sw}}{Q_H} \frac{\%CO_{2_w}}{100}$$

If, after calculating F_d, F_c, or F_w, a large discrepancy exists between the calculated value and the corresponding value in the table, the original data for Q_s, Q_H, and the O_2 or CO_2 data should be checked. This is essentially an easy way of conducting a material balance check.

Using a tabulated value for F_d, F_c, or F_w and the data obtained during the stack test for Q_s and $\%O_2$ or $\%CO_2$, a value for Q_H may be obtained from the equations.

If ultimate and proximate analyses are available, they may be used to calculate an F-factor using one of the equations. The calculated value can then be checked with the tabulated values and should be within 3 to 5 percent agreement, depending on the type of fuel and type of F-factor.

The F_o-factor may be used to check Orsat or continuous monitoring O_2, CO_2 data in the field.

The F_o-factor is the ratio

$$F_o = \frac{20.9}{100} \frac{F_d}{F_c}$$

and is equal to

$$F_o = \frac{20.9 - \%O_2}{\%CO_2}$$

the $\%O_2$ and $\%CO_2$ being obtained or adjusted to a dry basis. A value differing from those tabulated would necessitate a recheck of the O_2, CO_2 data.

Errors and Problems in the Use of F-Factors

The following factors may contribute to errors in reporting emissions by using F-factors:

- Deviations in the average or "midpoint" F-factor value itself.
- Errors in the Orsat analysis and the consequent $\%O_2$ and $\%CO_2$ values.
- Failure to have complete combustion of the fuel (complete combustion is assumed in the derivation of all of the F-factor methods).
- Loss of CO_2 when wet scrubbers are used – affecting the F_d, F_c, and F_w factors. Addition of CO_2 when lime or limestone scrubbers are used – affecting the F_c factor.
- Variations in B_{wa} for the wet F-factor method, F_w.

The deviations in the F-factors themselves have been found to vary no more than about 5 percent within a given fuel category. Since the F-factors given are averaged values, differences in the ultimate analysis between fuel samples could easily account for the deviation. The most significant problem in the use of the F-factors, however, is in the excess air correction. An error of a few percent in the O_2 or CO_2 concentration could cause a relatively large error in the value of E.

Since the F-factor method has been developed assuming complete combustion of the fuel, incomplete combustion will cause an error. However, if the CO is determined in the flue gas, some adjustment can be made to minimize this error.

$$(\%CO_2)_{adj} = \%CO_2 + \%CO$$

$$(\%O_2)_{adj} = \%O_2 - 0.5\ \%CO$$

By making these adjustments, the error amounts to minus one-half the concentration of CO present. However, this does not account for any unburned combustible matter. The F-factor methods would count the calorific value of this unburned fuel towards the heat input, and a positive bias would result in the calculated emission level.

APPENDIX D

TITLE 40 PART 60 APPENDIX B

CODE OF FEDERAL REGULATIONS 1977

PERFORMANCE SPECIFICATIONS

APPENDIX B—PERFORMANCE SPECIFICATIONS

Performance Specification 1—Performance specifications and specification test procedures for transmissometer systems for continuous measurement of the opacity of stack emissions.

1. Principle and Applicability.

1.1 Principle. The opacity of particulate matter in stack emissions is measured by a continuously operating emission measurement system. These systems are based upon the principle of transmissometry which is a direct measurement of the attenuation of visible radiation (opacity) by particulate matter in a stack effluent. Light having specific spectral characteristics is projected from a lamp across the stack of a pollutant source to a light sensor. The light is attenuated due to absorption and scatter by the particulate matter in the effluent. The percentage of visible light attenuated is defined as the opacity of the emission. Transparent stack emissions that do not attenuate light will have a transmittance of 100 or an opacity of 0. Opaque stack emissions that attenuate all of the visible light will have a transmittance of 0 or an opacity of 100 percent. The transmissometer is evaluated by use of neutral density filters to determine the precision of the continuous monitoring system. Tests of the system are performed to determine zero drift, calibration drift, and response time characteristics of the system.

1.2 Applicability. This performance specification is applicable to the continuous monitoring systems specified in the subparts for measuring opacity of emissions. Specifications for continuous measurement of visible emissions are given in terms of design, performance, and installation parameters. These specifications contain test procedures, installation requirements, and data computation procedures for evaluating the acceptability of the continuous monitoring systems subject to approval by the Administrator.

2. Apparatus.

2.1 Calibrated Filters. Optical filters with neutral spectral characteristics and known optical densities to visible light or screens known to produce specified optical densities. Calibrated filters with accuracies certified by the manufacturer to within ±3 percent opacity shall be used. Filters required are low, mid, and high-range filters with nominal optical densities as follows when the transmissometer is spanned at opacity levels specified by applicable subparts:

Span value (percent opacity)	Calibrated filter optical densities with equivalent opacity in parenthesis		
	Low-range	Mid-range	High-range
50	0.1 (20)	0.2 (37)	0.3 (50)
60	.1 (20)	.2 (37)	.3 (50)
70	.1 (20)	.3 (50)	.4 (60)
80	.1 (20)	.3 (50)	.6 (75)
90	.1 (20)	.4 (60)	.7 (80)
100	.1 (20)	.4 (60)	.9 (87½)

It is recommended that filter calibrations be checked with a well-collimated photopic transmissometer of known linearity prior to use. The filters shall be of sufficient size to attenuate the entire light beam of the transmissometer.

2.2 Data Recorder. Analog chart recorder or other suitable device with input voltage range compatible with the analyzer system output. The resolution of the recorder's data output shall be sufficient to allow completion of the test procedures within this specification.

2.3 Opacity measurement System. An instack transmissometer (folded or single path) with the optical design specifications designated below, associated control units and apparatus to keep optical surfaces clean.

3. Definitions.

3.1 Continuous Monitoring System. The total equipment required for the determination of pollutant opacity in a source effluent. Continuous monitoring systems consist of major subsystems as follows:

3.1.1 Sampling Interface. The portion of a continuous monitoring system for opacity that protects the analyzer from the effluent.

3.1.2 Analyzer. That portion of the continuous monitoring system which senses the pollutant and generates a signal output that is a function of the pollutant opacity.

3.1.3 Data Recorder. That portion of the continuous monitoring system that processes the analyzer output and provides a permanent record of the output signal in terms of pollutant opacity.

3.2 Transmissometer. The portions of a continuous monitoring system for opacity that include the sampling interface and the analyzer.

3.3 Span. The value of opacity at which the continuous monitoring system is set to produce the maximum data display output. The span shall be set at an opacity specified in each applicable subpart.

3.4 Calibration Error. The difference between the opacity reading indicated by the continuous monitoring system and the known values of a series of test standards. For this method the test standards are a series of calibrated optical filters or screens.

3.5 Zero Drift. The change in continuous monitoring system output over a stated period of time of normal continuous operation when the pollutant concentration at the time of the measurements is zero.

3.6 Calibration Drift. The change in the continuous monitoring system output over a stated period of time of normal continuous operation when the pollutant concentration at the time of the measurements is the same known upscale value.

3.7 System Response. The time interval from a step change in opacity in the stack at the input to the continuous monitoring system to the time at which 95 percent of the corresponding final value is reached as displayed on the continuous monitoring system data recorder.

3.8 Operational Test Period. A minimum period of time over which a continuous monitoring system is expected to operate within certain performance specifications without unscheduled maintenance, repair, or adjustment.

3.9 Transmittance. The fraction of incident light that is transmitted through an optical medium of interest.

3.10 Opacity. The fraction of incident light that is attenuated by an optical medium of interest. Opacity (O) and transmittance (T) are related as follows:

$$O=1-T$$

3.11 Optical Density. A logarithmic measure of the amount of light that it attenuated by an optical medium of interest. Optical density (D) is related to the transmittance and opacity as follows:

$$D=-\log_{10} T$$

$$D=-\log_{10} (1-O)$$

3.12 Peak Optical Response. The wavelength of maximum sensitivity of the instrument.

3.13 Mean Spectral Response. The wavelength which bisects the total area under the curve obtained pursuant to paragraph 9.2.1.

3.14 Angle of View. The maximum (total) angle of radiation detection by the photodetector assembly of the analyzer.

3.15 Angle of Projection. The maximum (total) angle that contains 95 percent of the radiation projected from the lamp assembly of the analyzer.

3.16 Pathlength. The depth of effluent in the light beam between the receiver and the transmitter of the single-pass transmissometer, or the depth of effluent between the transceiver and reflector of a double-pass transmissometer. Two pathlengths are referenced by this specification:

3.16.1 Monitor Pathlength. The depth of effluent at the installed location of the continuous monitoring system.

3.16.2 Emission Outlet Pathlength. The depth of effluent at the location emissions are released to the atmosphere.

4. Installation Specification.

4.1 Location. The transmissometer must be located across a section of duct or stack that will provide a particulate matter flow through the optical volume of the transmissometer that is representative of the particulate matter flow through the duct or stack. It is recommended that the monitor pathlength or depth of effluent for the transmissometer include the entire diameter of the duct or stack. In installations using a shorter pathlength, extra caution must be used in determining the measurement location representative of the particulate matter flow through the duct or stack.

4.1.1 The transmissometer location shall be downstream from all particulate control equipment.

4.1.2 The transmissometer shall be located as far from bends and obstructions as practical.

4.1.3 A transmissometer that is located in the duct or stack following a bend shall be installed in the plane defined by the bend where possible.

4.1.4 The transmissometer should be installed in an accessible location.

4.1.5 When required by the Administrator, the owner or operator of a source must demonstrate that the transmissometer is located in a section of duct or stack where a representative particulate matter distribution exists. The determination shall be accomplished by examining the opacity profile of the effluent at a series of positions across the duct or stack while the plant is in operation at maximum or reduced operating rates or by other tests acceptable to the Administrator.

4.2 Slotted Tube. Installations that require the use of a slotted tube shall use a slotted tube of sufficient size and blackness so as not to interfere with the free flow of effluent through the entire optical volume of the transmissometer or reflect light into the transmissometer photodetector. Light reflections may be prevented by using blackened baffles within the slotted tube to prevent the lamp radiation from impinging upon the tube walls, by restricting the angle of projection of the light and the angle of view of the photodetector assembly to less than the cross-sectional area of the slotted tube, or by other methods. The owner or operator must show that the manufacturer of the monitoring system has used appropriate methods to minimize light reflections for systems using slotted tubes.

4.3 Data Recorder Output. The continuous monitoring system output shall permit expanded display of the span opacity on a standard 0 to 100 percent scale. Since all opacity standards are based on the opacity of the effluent exhausted to the atmosphere, the system output shall be based upon the emission outlet pathlength and permanently recorded. For affected facilities whose monitor pathlength is different from the facility's emission outlet pathlength, a graph shall be provided with the installation to show the relationships between the continuous monitoring system recorded opacity based upon the emission outlet pathlength and the opacity of the effluent at the analyzer location (monitor pathlength). Tests for measurement of opacity that are required by this performance specification are based upon the monitor pathlength. The graph necessary to convert the data recorder output to the monitor pathlength basis shall be established as follows:

$$\log (1-0_1)=(1_1/1_2)\log (1-0_2)$$

where:

0_1 = the opacity of the effluent based upon 1_1.
0_2 = the opacity of the effluent based upon 1_2.
1_1 = the emission outlet pathlength.
1_2 = the monitor pathlength.

5. Optical Design Specifications.

The optical design specifications set forth in Section 6.1 shall be met in order for a measurement system to comply with the requirements of this method.

6. Determination of Conformance with Design Specifications.

6.1 The continuous monitoring system for measurement of opacity shall be demonstrated to conform to the design specifications set forth as follows:

6.1.1 Peak Spectral Response. The peak spectral response of the continuous monitoring systems shall occur between 500 nm and 600 nm. Response at any wavelength below 400 nm or above 700 nm shall be less than 10 percent of the peak response of the continuous monitoring system.

6.1.2 Mean Spectral Response. The mean spectral response of the continuous monitoring system shall occur between 500 nm and 600 nm.

6.1.3 Angle of View. The total angle of view shall be no greater than 5 degrees.

6.1.4 Angle of Projection. The total angle of projection shall be no greater than 5 degrees.

6.2 Conformance with the requirements of section 6.1 may be demonstrated by the owner or operator of the affected facility by testing each analyzer or by obtaining a certificate of conformance from the instrument manufacturer. The certificate must certify that at least one analyzer from each month's production was tested and satisfactorily met all applicable requirements. The certificate must state that the first analyzer randomly sampled met all requirements of paragraph 6 of this specification. If any of the requirements were not met, the certificate must show that the entire month's analyzer production was resampled according to the military standard 105D sampling procedure (MIL–STD–105D) inspection level II; was retested for each of the applicable requirements under paragraph 6 of this specification; and was determined to be acceptable under MIL–STD–105D procedures. The certificate of conformance must show the results of each test performed for the analyzers sampled during the month the analyzer being installed was produced.

6.3 The general test procedures to be followed to demonstrate conformance with Section 6 requirements are given as follows: (These procedures will not be applicable to all designs and will require modification in some cases. Where analyzer and optical design is certified by the manufacturer to conform with the angle of view or angle of projection specifications, the respective procedures may be omitted.)

6.3.1 Spectral Response. Obtain spectral data for detector, lamp, and filter components used in the measurement system from their respective manufacturers.

6.3.2 Angle of View. Set the receiver up as specified by the manufacturer. Draw an arc with radius of 3 meters. Measure the receiver response to a small (less than 3 centimeters) non-directional light source at 5-centimeter intervals on the arc for 26 centimeters on either side of the detector centerline. Repeat the test in the vertical direction.

6.3.3 Angle of Projection. Set the projector up as specified by the manufacturer. Draw an arc with radius of 3 meters. Using a small photoelectric light detector (less than 3 centimeters), measure the light intensity at 5-centimeter intervals on the arc for 26 centimeters on either side of the light source centerline of projection. Repeat the test in the vertical direction.

7. Continuous Monitoring System Performance Specifications.

The continuous monitoring system shall meet the performance specifications in Table 1–1 to be considered acceptable under this method.

TABLE 1–1.—*Performance specifications*

Parameter	*Specifications*
a. Calibration error	$\leq$3 pct opacity.[1]
b. Zero drift (24 h)	$\leq$2 pct opacity.[1]
c. Calibration drift (24 h)	$\leq$2 pct opacity.[1]
d. Response time	10 s (maximum).
e. Operational test period	168 h.

[1] Expressed as sum of absolute mean value and the 95 pct confidence interval of a series of tests.

8. Performance Specification Test Procedures. The following test procedures shall be used to determine conformance with the requirements of paragraph 7:

8.1 Calibration Error and Response Time Test. These tests are to be performed prior to installation of the system on the stack and may be performed at the affected facility or at other locations provided that proper notification is given. Set up and calibrate the measurement system as specified by the manufacturer's written instructions for the monitor pathlength to be used in the installation. Span the analyzer as specified in applicable subparts.

8.1.1 Calibration Error Test. Insert a series of calibration filters in the transmissometer path at the midpoint. A minimum of three calibration filters (low, mid, and high-range) selected in accordance with the table under paragraph 2.1 and calibrated within 3 percent must be used. Make a total of five nonconsecutive readings for each filter. Record the measurement system output readings in percent opacity. (See Figure 1–1.)

8.1.2 System Response Test. Insert the high-range filter in the transmissometer path five times and record the time required for the system to respond to 95 percent of final zero and high-range filter values. (See Figure 1–2.)

8.2 Field Test for Zero Drift and Calibration Drift. Install the continuous monitoring system on the affected facility and perform the following alignments:

8.2.1 Preliminary Alignments. As soon as possible after installation and once a year thereafter when the facility is not in operation, perform the following optical and zero alignments:

8.2.1.1 Optical Alignment. Align the light beam from the transmissometer upon the optical surfaces located across the effluent (i.e., the retroflector or photodetector as applicable) in accordance with the manufacturer's instructions.

8.2.1.2 Zero Alignment. After the transmissometer has been optically aligned and the transmissometer mounting is mechanically stable (i.e., no movement of the mounting due to thermal contraction of the stack, duct, etc.) and a clean stack condition has been determined by a steady zero opacity condition, perform the zero alignment. This alignment is performed by balancing the continuous monitor system response so that any simulated zero check coincides with an actual zero check performed across the monitor pathlength of the clean stack.

8.2.1.3 Span. Span the continuous monitoring system at the opacity specified in subparts and offset the zero setting at least 10 percent of span so that negative drift can be quantified.

8.2.2. Final Alignments. After the preliminary alignments have been completed and the affected facility has been started up and reaches normal operating temperature, recheck the optical alignment in accordance with 8.2.1.1 of this specification. If the alignment has shifted, realign the optics, record any detectable shift in the opacity measured by the system that can be attributed to the optical realignment, and notify the Administrator. This condition may not be objectionable if the affected facility operates within a fairly constant and adequately narrow range of operating temperatures that does not produce significant shifts in optical alignment during normal operation of the facility. Under circumstances where the facility operations produce fluctuations in the effluent gas temperature that result in significant misalignments, the Administrator may require improved mounting structures or another location for installation of the transmissometer.

8.2.3 Conditioning Period. After completing the post-startup alignments, operate the system for an initial 168-hour conditioning period in a normal operational manner.

8.2.4 Operational Test Period. After completing the conditioning period, operate the system for an additional 168-hour period retaining the zero offset. The system shall monitor the source effluent at all times except when being zeroed or calibrated. At 24-hour intervals the zero and span shall be checked according to the manufacturer's instructions. Minimum procedures used shall provide a system check of the analyzer internal mirrors and all electronic circuitry including the lamp and photodetector assembly and shall include a procedure for producing a simulated zero opacity condition and a simulated upscale (span) opacity condition as viewed by the receiver. The manufacturer's written instructions may be used providing that they equal or exceed these minimum procedures. Zero and span the transmissometer, clean all optical surfaces exposed to the effluent, realign optics, and make any necessary adjustments to the calibration of the system daily. These zero and calibration adjustments and optical realignments are allowed only at 24-hour intervals or at such shorter intervals as the manufacturer's written instructions specify. Automatic corrections made by the measurement system without operator intervention are allowable at any time. The magnitude of any zero or span drift adjustments shall be recorded. During this 168-hour operational test period, record the following at 24-hour intervals: (a) The zero reading and span readings after the system is calibrated (these readings should be set at the same value at the beginning of each 24-hour period); (b) the zero reading after each 24 hours of operation, but before cleaning and adjustment; and (c) the span reading after cleaning and zero adjustment, but before span adjustment. (See Figure 1–3.)

9. Calculation, Data Analysis, and Reporting.

9.1 Procedure for Determination of Mean Values and Confidence Intervals.

9.1.1 The mean value of the data set is calculated according to equation 1–1.

$$\bar{x}=\frac{1}{n}\sum_{i=1}^{n}x_i \qquad \text{Equation 1–1}$$

where x_i = absolute value of the individual measurements,

Σ = sum of the individual values.
$\bar{x}$ = mean value, and
n = number of data points.

9.1.2 The 95 percent confidence interval (two-sided) is calculated according to equation 1-2:

$$C.I._{95} = \frac{t_{.975}}{n\sqrt{n-1}} \sqrt{n(\sum x_i^2) - (\sum x_i)^2}$$

Equation 1-2

where
$\sum x_i$ = sum of all data points,
$t_{.975} = t_1 - \alpha/2$, and
$C.I._{95}$ = 95 percent confidence interval estimate of the average mean value.

Values for $t_{.975}$

n	$t_{.975}$	n	$t_{.975}$
2	12.706	10	2.262
3	4.303	11	2.228
4	3.182	12	2.201
5	2.776	13	2.179
6	2.571	14	2.160
7	2.447	15	2.145
8	2.365	16	2.131
9	2.306		

The values in this table are already corrected for n-1 degrees of freedom. Use n equal to the number of samples as data points.

9.2 Data Analysis and Reporting.

9.2.1 Spectral Response. Combine the spectral data obtained in accordance with paragraph 6.3.1 to develop the effective spectral response curve of the transmissometer. Report the wavelength at which the peak response occurs, the wavelength at which the mean response occurs, and the maximum response at any wavelength below 400 nm and above 700 nm expressed as a percentage of the peak response as required under paragraph 6.2.

9.2.2 Angle of View. Using the data obtained in accordance with paragraph 6.3.2, calculate the response of the receiver as a function of viewing angle in the horizontal and vertical directions (26 centimeters of arc with a radius of 3 meters equal 5 degrees). Report relative angle of view curves as required under paragraph 6.2.

9.2.3 Angle of Projection. Using the data obtained in accordance with paragraph 6.3.3, calculate the response of the photoelectric detector as a function of projection angle in the horizontal and vertical directions. Report relative angle of projection curves as required under paragraph 6.2.

9.2.4 Calibration Error. Using the data from paragraph 8.1 (Figure 1-1), subtract the known filter opacity value from the value shown by the measurement system for each of the 15 readings. Calculate the mean and 95 percent confidence interval of the five different values at each test filter value according to equations 1-1 and 1-2. Report the sum of the absolute mean difference and the 95 percent confidence interval for each of the three test filters.

9.2.5 Zero Drift. Using the zero opacity values measured every 24 hours during the field test (paragraph 8.3), calculate the differences between the zero point after cleaning, aligning, and adjustment, and the zero value 24 hours later just prior to cleaning, aligning, and adjustment. Calculate the mean value of these points and the confidence interval using equations 1-1 and 1-2. Report the sum of the absolute mean value and the 95 percent confidence interval.

9.2.6 Calibration Drift. Using the span value measured every 24 hours during the field test, calculate the differences between the span value after cleaning, aligning, and adjustment of zero and span, and the span value 24 hours later just after cleaning, aligning, and adjustment of zero and before adjustment of span. Calculate the mean value of these points and the confidence interval using equations 1-1 and 1-2. Report the sum of the absolute mean value and the confidence interval.

9.2.7 Response Time. Using the data from paragraph 8.1, calculate the time interval from filter insertion to 95 percent of the final stable value for all upscale and downscale traverses. Report the mean of the 10 upscale and downscale test times.

9.2.8 Operational Test Period. During the 168-hour operational test period, the continuous monitoring system shall not require any corrective maintenance, repair, replacement, or adjustment other than that clearly specified as required in the manufacturer's operation and maintenance manuals as routine and expected during a one-week period. If the continuous monitoring system is operated within the specified performance parameters and does not require corrective maintenance, repair, replacement, or adjustment other than as specified above during the 168-hour test period, the operational test period shall have been successfully concluded. Failure of the continuous monitoring system to meet these requirements shall call for a repetition of the 168-hour test period. Portions of the tests which were satisfactorily completed need not be repeated. Failure to meet any performance specification(s) shall call for a repetition of the one-week operational test period and that specific portion of the tests required by paragraph 8 related to demonstrating compliance with the failed specification. All maintenance and adjustments required shall be recorded. Output readings shall be recorded before and after all adjustments.

10. References.

10.1 "Experimental Statistics," Department of Commerce, National Bureau of Standards Handbook 91, 1963, pp. 3-31, paragraphs 3-3.1.4.

10.2 "Performance Specifications for Stationary-Source Monitoring Systems for Gases and Visible Emissions," Environmental Protection Agency, Research Triangle Park, N.C., EPA-650/2-74-013, January 1974.

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Calibrated Neutral Density Filter Data
(See paragraph 8.1.1)

Low Range ____% opacity Span Value ____% opacity	Mid Range ___% opacity		High Range ___% opacity
Date of Test ____________	Location of Test ____________		
	Calibrated Filter[1]	Analyzer Reading % Opacity	Differences[2] % Opacity
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			

	Low	Mid	High
Mean difference	___	___	___
Confidence interval	___	___	___
Calibration error = Mean Difference[3] + C.I.	___	___	___

---

[1] Low, mid or high range
[2] Calibration filter opacity - analyzer reading
[3] Absolute value

Figure 1-1. Calibration Error Test

Date of Test ____________ Location of Test ____________

Span Filter ____________ % Opacity

Analyzer Span Setting ____________ % Opacity

Upscale 1 ____________ seconds
2 ____________ seconds
3 ____________ seconds
4 ____________ seconds
5 ____________ seconds

Downscale 1 ____________ seconds
2 ____________ seconds
3 ____________ seconds
4 ____________ seconds
5 ____________ seconds

Average response ____________ seconds

Figure 1-2. Response Time Test

Zero Setting ____________ (See paragraph 8.2.1) Date of Test ____________

Span Setting ____________

Date and Time	Zero Reading (Before cleaning and adjustment)	Zero Drift (ΔZero)	Span Reading (After cleaning and zero adjustment but before span adjustment)	Calibration Drift (ΔSpan)

Zero Drift = Mean Zero Drift* ____________ + CI (Zero) ____________ = ____________.

Calibration Drift = Mean Span Drift* ____________ + CI (Span) ____________ = ____________.

---

*Absolute value

Figure 1-3. Zero and Calibration Drift Test

PERFORMANCE SPECIFICATION 2—PERFORMANCE SPECIFICATIONS AND SPECIFICATION TEST PROCEDURES FOR MONITORS OF SO_2 AND NO_x FROM STATIONARY SOURCES

1. Principle and Applicability.

1.1 Principle. The concentration of sulfur dioxide or oxides of nitrogen pollutants in stack emissions is measured by a continuously operating emission measurement system. Concurrent with operation of the continuous monitoring system, the pollutant concentrations are also measured with reference methods (Appendix A). An average of the continuous monitoring system data is computed for each reference method testing period and compared to determine the relative accuracy of the continuous monitoring system. Other tests of the continuous monitoring system are also performed to determine calibration error, drift, and response characteristics of the system.

1.2 Applicability. This performance specification is applicable to evaluation of continuous monitoring systems for measurement of nitrogen oxides or sulfur dioxide pollutants. These specifications contain test procedures, installation requirements, and data computation procedures for evaluating the acceptability of the continuous monitoring systems.

2. Apparatus.

2.1 Calibration Gas Mixtures. Mixtures of known concentrations of pollutant gas in a diluent gas shall be prepared. The pollutant gas shall be sulfur dioxide or the appropriate oxide(s) of nitrogen specified by paragraph 6 and within subparts. For sulfur dioxide gas mixtures, the diluent gas may be air or nitrogen. For nitric oxide (NO) gas mixtures, the diluent gas shall be oxygen-free (<10 ppm) nitrogen, and for nitrogen dioxide (NO_2) gas mixtures the diluent gas shall be air. Concentrations of approximately 50 percent and 90 percent of span are required. The 90 percent gas mixture is used to set and to check the span and is referred to as the span gas.

2.2 Zero Gas. A gas certified by the manufacturer to contain less than 1 ppm of the pollutant gas or ambient air may be used.

2.3 Equipment for measurement of the pollutant gas concentration using the reference method specified in the applicable standard.

2.4 Data Recorder. Analog chart recorder or other suitable device with input voltage range compatible with analyzer system output. The resolution of the recorder's data output shall be sufficient to allow completion of the test procedures within this specification.

2.5 Continuous monitoring system for SO_2 or NO_x pollutants as applicable.

3. Definitions.

3.1 Continuous Monitoring System. The total equipment required for the determination of a pollutant gas concentration in a source effluent. Continuous monitoring systems consist of major subsystems as follows:

3.1.1 Sampling Interface. That portion of an extractive continuous monitoring system that performs one or more of the following operations: Acquisition, transportation, and conditioning of a sample of the source effluent or that portion of an in-situ continuous monitoring system that protects the analyzer from the effluent.

3.1.2 Analyzer. That portion of the continuous monitoring system which senses the pollutant gas and generates a signal output that is a function of the pollutant concentration.

3.1.3 Data Recorder. That portion of the continuous monitoring system that provides a permanent record of the output signal in terms of concentration units.

3.2 Span. The value of pollutant concentration at which the continuous monitoring system is set to produce the maximum data display output. The span shall be set at the concentration specified in each applicable subpart.

3.3 Accuracy (Relative). The degree of correctness with which the continuous monitoring system yields the value of gas concentration of a sample relative to the value given by a defined reference method. This accuracy is expressed in terms of error, which is the difference between the paired concentration measurements expressed as a percentage of the mean reference value.

3.4 Calibration Error. The difference between the pollutant concentration indicated by the continuous monitoring system and the known concentration of the test gas mixture.

3.5 Zero Drift. The change in the continuous monitoring system output over a stated period of time of normal continuous operation when the pollutant concentration at the time for the measurements is zero.

3.6 Calibration Drift. The change in the continuous monitoring system output over a stated time period of normal continuous operations when the pollutant concentration at the time of the measurements is the same known upscale value.

3.7 Response Time. The time interval from a step change in pollutant concentration at the input to the continuous monitoring system to the time at which 95 percent of the corresponding final value is reached as displayed on the continuous monitoring system data recorder.

3.8 Operational Period. A minimum period of time over which a measurement system is expected to operate within certain performance specifications without unscheduled maintenance, repair, or adjustment.

3.9 Stratification. A condition identified by a difference in excess of 10 percent between the average concentration in the duct or stack and the concentration at any point more than 1.0 meter from the duct or stack wall.

4. Installation Specifications. Pollutant continuous monitoring systems (SO_2 and NO_x) shall be installed at a sampling location where measurements can be made which are directly representative (4.1), or which can be corrected so as to be representative (4.2) of the total emissions from the affected

facility. Conformance with this requirement shall be accomplished as follows:

4.1 Effluent gases may be assumed to be nonstratified if a sampling location eight or more stack diameters (equivalent diameters) downstream of any air in-leakage is selected. This assumption and data correction procedures under paragraph 4.2.1 may not be applied to sampling locations upstream of an air preheater in a steam generating facility under Subpart D of this part. For sampling locations where effluent gases are either demonstrated (4.3) or may be assumed to be nonstratified (eight diameters), a point (extractive systems) or path (in-situ systems) of average concentration may be monitored.

4.2 For sampling locations where effluent gases cannot be assumed to be nonstratified (less than eight diameters) or have been shown under paragraph 4.3 to be stratified, results obtained must be consistently representative (e.g. a point of average concentration may shift with load changes) or the data generated by sampling at a point (extractive systems) or across a path (in-situ systems) must be corrected (4.2.1 and 4.2.2) so as to be representative of the total emissions from the affected facility. Conformance with this requirement may be accomplished in either of the following ways:

4.2.1 Installation of a diluent continuous monitoring system (O_2 or CO_2 as applicable) in accordance with the procedures under paragraph 4.2 of Performance Specification 3 of this appendix. If the pollutant and diluent monitoring systems are not of the same type (both extractive or both in-situ), the extractive system must use a multipoint probe.

4.2.2 Installation of extractive pollutant monitoring systems using multipoint sampling probes or in-situ pollutant monitoring systems that sample or view emissions which are consistently representative of the total emissions for the entire cross section. The Administrator may require data to be submitted to demonstrate that the emissions sampled or viewed are consistently representative for several typical facility process operating conditions.

4.3 The owner or operator may perform a traverse to characterize any stratification of effluent gases that might exist in a stack or duct. If no stratification is present, sampling procedures under paragraph 4.1 may be applied even though the eight diameter criteria is not met.

4.4 When single point sampling probes for extractive systems are installed within the stack or duct under paragraphs 4.1 and 4.2.1, the sample may not be extracted at any point less than 1.0 meter from the stack or duct wall. Multipoint sampling probes installed under paragraph 4.2.2 may be located at any points necessary to obtain consistently representative samples.

5. Continuous Monitoring System Performance Specifications.

The continuous monitoring system shall meet the performance specifications in Table 2-1 to be considered acceptable under this method.

TABLE 2-1.—*Performance specifications*

Parameter	Specification
1. Accuracy [1]	≤20 pct of the mean value of the reference method test data.
2. Calibration error [1]	≤ 5 pct of each (50 pct, 90 pct) calibration gas mixture value.
3. Zero drift (2 h) [1]	2 pct of span
4. Zero drift (24 h) [1]	Do.
5. Calibration drift (2 h) [1]	Do.
6. Calibration drift (24 h) [1]	2.5 pct. of span
7. Response time	15 min maximum.
8. Operational period	168 h minimum.

[1] Expressed as sum of absolute mean value plus 95 pct confidence interval of a series of tests.

6. **Performance Specification Test Procedures. The following test procedures shall be** used to determine conformance with the requirements of paragraph 5. For NO_x analyzers that oxidize nitric oxide (NO) to nitrogen dioxide (NO_2), the response time test under paragraph 6.3 of this method shall be performed using nitric oxide (NO) span gas. Other tests for NO_x continuous monitoring systems under paragraphs 6.1 and 6.2 and all tests for sulfur dioxide systems shall be performed using the pollutant span gas specified by each subpart.

6.1 Calibration Error Test Procedure. Set up and calibrate the complete continuous monitoring system according to the manufacturer's written instructions. This may be accomplished either in the laboratory or in the field.

6.1.1 Calibration Gas Analyses. Triplicate analyses of the gas mixtures shall be performed within two weeks prior to use using Reference Methods 6 for SO_2 and 7 for NO_x. Analyze each calibration gas mixture (50%, 90%) and record the results on the example sheet shown in Figure 2-1. Each sample test result must be within 20 percent of the averaged result or the tests shall be repeated. This step may be omitted for non-extractive monitors where dynamic calibration gas mixtures are not used (6.1.2).

6.1.2 Calibration Error Test Procedure. Make a total of 15 nonconsecutive measurements by alternately using zero gas and each calibration gas mixture concentration (e.g., 0%, 50%, 0%, 90%, 50%, 90%, 50%, 0%, etc.). For nonextractive continuous monitoring systems, this test procedure may be performed by using two or more calibration gas cells whose concentrations are certified by the manufacturer to be functionally equivalent to these gas concentrations. Convert the continuous monitoring system output readings to ppm and record the results on the example sheet shown in Figure 2-2.

6.2 Field Test for Accuracy (Relative), Zero Drift, and Calibration Drift. Install and operate the continuous monitoring system in accordance with the manufacturer's written instructions and drawings as follows:

6.2.1 Conditioning Period. Offset the zero setting at least 10 percent of the span so that negative zero drift can be quantified. Operate the system for an initial 168-hour conditioning period in normal operating manner.

6.2.2 Operational Test Period. Operate the continuous monitoring system for an additional 168-hour period retaining the zero offset. The system shall monitor the source effluent at all times except when being zeroed, calibrated, or backpurged.

6.2.2.1 Field Test for Accuracy (Relative). For continuous monitoring systems employing extractive sampling, the probe tip for the continuous monitoring system and the probe tip for the Reference Method sampling train should be placed at adjacent locations in the duct. For NO_x continuous monitoring systems, make 27 NO_x concentration measurements, divided into nine sets, using the applicable reference method. No more than one set of tests, consisting of three individual measurements, shall be performed in any one hour. All individual measurements of each set shall be performed concurrently, or within a three-minute interval and the results averaged. For SO_2 continuous monitoring systems, make nine SO_2 concentration measurements using the applicable reference method. No more than one measurement shall be performed in any one hour. Record the reference method test data and the continuous monitoring system concentrations on the example data sheet shown in Figure 2-3.

6.2.2.2 Field Test for Zero Drift and Calibration Drift. For extractive systems, determine the values given by zero and span gas pollutant concentrations at two-hour intervals until 15 sets of data are obtained. For nonextractive measurement systems, the zero value may be determined by mechanically producing a zero condition that provides a system check of the analyzer internal mirrors and all electronic circuitry including the radiation source and detector assembly or by inserting three or more calibration gas cells and computing the zero point from the upscale measurements. If this latter technique is used, a graph(s) must be retained by the owner or operator for each measurement system that shows the relationship between the upscale measurements and the zero point. The span of the system shall be checked by using a calibration gas cell certified by the manufacturer to be functionally equivalent to 50 percent of span concentration. Record the zero and span measurements (or the computed zero drift) on the example data sheet shown in Figure 2-4. The two-hour periods over which measurements are conducted need not be consecutive but may not overlap. All measurements required under this paragraph may be conducted concurrent with tests under paragraph 6.2.2.1.

6.2.2.3 Adjustments. Zero and calibration corrections and adjustments are allowed only at 24-hour intervals or at such shorter intervals as the manufacturer's written instructions specify. Automatic corrections made by the measurement system without operator intervention or initiation are allowable at any time. During the entire 168-hour operational test period, record on the example sheet shown in Figure 2-5 the values given by zero and span gas pollutant concentrations before and after adjustment at 24-hour intervals.

6.3 Field Test for Response Time.

6.3.1 Scope of Test. Use the entire continuous monitoring system as installed, including sample transport lines if used. Flow rates, line diameters, pumping rates, pressures (do not allow the pressurized calibration gas to change the normal operating pressure in the sample line), etc., shall be at the nominal values for normal operation as specified in the manufacturer's written instructions. If the analyzer is used to sample more than one pollutant source (stack), repeat this test for each sampling point.

6.3.2 Response Time Test Procedure. Introduce zero gas into the continuous monitoring system sampling interface or as close to the sampling interface as possible. When the system output reading has stabilized, switch quickly to a known concentration of pollutant gas. Record the time from concentration switching to 95 percent of final stable response. For non-extractive monitors, the highest available calibration gas concentration shall be switched into and out of the sample path and response times recorded. Perform this test sequence three (3) times. Record the results of each test on the example sheet shown in Figure 2-6.

7. Calculations, Data Analysis and Reporting.

7.1 Procedure for determination of mean values and confidence intervals.

7.1.1 The mean value of a data set is calculated according to equation 2-1.

$$\bar{x}=\frac{1}{n}\sum_{i=1}^{n} x_i$$

Equation 2-1

where:

x_i = absolute value of the measurements,
Σ = sum of the individual values,
x = mean value, and
n = number of data points.

7.1.2 The 95 percent confidence interval (two-sided) is calculated according to equation 2-2:

$$C.I._{95}=\frac{t_{.975}}{n\sqrt{n-1}}\sqrt{n(\Sigma x_i^2)-(\Sigma x_i)^2}$$

Equation 2-2

where:

$\sum x_i$ = sum of all data points,

$t_{.975} = t_1 - \alpha/2$, and

$C.I._{.95}$ = 95 percent confidence interval estimate of the average mean value.

Values for $t_{.975}$

n	$t_{.975}$
2	12.706
3	4.303
4	3.182
5	2.776
6	2.571
7	2.447
8	2.365
9	2.306
10	2.262
11	2.228
12	2.201
13	2.179
14	2.160
15	2.145
16	2.131

The values in this table are already corrected for n-1 degrees of freedom. Use n equal to the number of samples as data points.

7.2 Data Analysis and Reporting.

7.2.1 Accuracy (Relative). For each of the nine reference method test points, determine the average pollutant concentration reported by the continuous monitoring system. These average concentrations shall be determined from the continuous monitoring system data recorded under 7.2.2 by integrating or averaging the pollutant concentrations over each of the time intervals concurrent with each reference method testing period. Before proceeding to the next step, determine the basis (wet or dry) of the continuous monitoring system data and reference method test data concentrations. If the bases are not consistent, apply a moisture correction to either reference method concentrations or the continuous monitoring system concentrations as appropriate. Determine the correction factor by moisture tests concurrent with the reference method testing periods. Report the moisture test method and the correction procedure employed. For each of the nine test runs determine the difference for each test run by subtracting the respective reference method test concentrations (use average of each set of three measurements for NO_x) from the continuous monitoring system integrated or averaged concentrations. Using these data, compute the mean difference and the 95 percent confidence interval of the differences (equations 2-1 and 2-2). Accuracy is reported as the sum of the absolute value of the mean difference and the 95 percent confidence interval of the differences expressed as a percentage of the mean reference method value. Use the example sheet shown in Figure 2-3.

7.2.2 Calibration Error. Using the data from paragraph 6.1, subtract the measured pollutant concentration determined under paragraph 6.1.1 (Figure 2-1) from the value shown by the continuous monitoring system for each of the five readings at each concentration measured under 6.1.2 (Figure 2-2). Calculate the mean of these difference values and the 95 percent confidence intervals according to equations 2-1 and 2-2. Report the calibration error (the sum of the absolute value of the mean difference and the 95 percent confidence interval) as a percentage of each respective calibration gas concentration. Use example sheet shown in Figure 2-2.

7.2.3 Zero Drift (2-hour). Using the zero concentration values measured each two hours during the field test, calculate the differences between consecutive two-hour readings expressed in ppm. Calculate the mean difference and the confidence interval using equations 2-1 and 2-2. Report the zero drift as the sum of the absolute mean value and the confidence interval as a percentage of span. Use example sheet shown in Figure 2-4.

7.2.4 Zero Drift (24-hour). Using the zero concentration values measured every 24 hours during the field test, calculate the differences between the zero point after zero adjustment and the zero value 24 hours later just prior to zero adjustment. Calculate the mean value of these points and the confidence interval using equations 2-1 and 2-2. Report the zero drift (the sum of the absolute mean and confidence interval) as a percentage of span. Use example sheet shown in Figure 2-5.

7.2.5 Calibration Drift (2-hour). Using the calibration values obtained at two-hour intervals during the field test, calculate the differences between consecutive two-hour readings expressed as ppm. These values should be corrected for the corresponding zero drift during that two-hour period. Calculate the mean and confidence interval of these corrected difference values using equations 2-1 and 2-2. Do not use the differences between non-consecutive readings. Report the calibration drift as the sum of the absolute mean and confidence interval as a percentage of span. Use example sheet shown in in Figure 2-4.

7.2.6 Calibration Drift (24-hour). Using the calibration values measured every 24 hours during the field test, calculate the differences between the calibration concentration reading after zero and calibration adjustment, and the calibration concentration reading 24 hours later after zero adjustment but before calibration adjustment. Calculate the mean value of these differences and the confidence interval using equations 2-1 and 2-2. Report the calibration drift (the sum of the absolute mean and confidence interval) as a percentage of span. Use the example sheet shown in Figure 2-5.

7.2.7 Response Time. Using the charts from paragraph 6.3, calculate the time interval from concentration switching to 95 percent to the final stable value for all upscale and downscale tests. Report the mean of the three upscale test times and the mean of the three downscale test times. The two average times should not differ by more than 15 percent of the slower time. Report the slower time as the system response time. Use the example sheet shown in Figure 2-6.

7.2.8 Operational Test Period. During the 168-hour performance and operational test period, the continuous monitoring system shall not require any corrective maintenance, repair, replacement, or adjustment other than that clearly specified as required in the operation and maintenance manuals as routine and expected during a one-week period. If the continuous monitoring system operates within the specified performance parameters and does not require corrective maintenance, repair, replacement or adjustment other than as specified above during the 168-hour test period, the operational period will be successfully concluded. Failure of the continuous monitoring system to meet this requirement shall call for a repetition of the 168-hour test period. Portions of the test which were satisfactorily completed need not be repeated. Failure to meet any performance specifications shall call for a repetition of the one-week performance test period and that portion of the testing which is related to the failed specification. All maintenance and adjustments required shall be recorded. Output readings shall be recorded before and after all adjustments.

8. References.

8.1 "Monitoring Instrumentation for the Measurement of Sulfur Dioxide in Stationary Source Emissions," Environmental Protection Agency, Research Triangle Park, N.C., February 1973.

8.2 "Instrumentation for the Determination of Nitrogen Oxides Content of Stationary Source Emissions," Environmental Protection Agency, Research Triangle Park, N.C., Volume 1, APTD-0847, October 1971; Volume 2, APTD-0942, January 1972.

8.3 "Experimental Statistics," Department of Commerce, Handbook 91, 1963, pp. 3-31, paragraphs 3-3.1.4.

8.4 "Performance Specifications for Stationary-Source Monitoring Systems for Gases and Visible Emissions," Environmental Protection Agency, Research Triangle Park, N.C., EPA-650/2-74-013, January 1974.

Date ________ Reference Method Used ____

Mid-Range Calibration Gas Mixture

Sample 1 ________ppm

Sample 2 ________ppm

Sample 3 ________ppm

Average ________ppm

High-Range (span) Calibration Gas Mixture

Sample 1 ________ppm

Sample 2 ________ppm

Sample 3 ________ppm

Average ________ppm

Figure 2-1. Analysis of Calibration Gas Mixtures

Calibration Gas Mixture Data (From Figure 2-1)

Mid (50%) _____ppm High (90%) _____ppm

Run #	Calibration Gas Concentration, ppm	Measurement System Reading, ppm	Differences,[1] ppm
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			

	Mid	High
Mean difference		
Confidence interval	_____	_____
Calibration error = $\frac{\text{Mean Difference}^2 + \text{C.I.}}{\text{Average Calibration Gas Concentration}}$ x 100	± _____ _____%	± _____ _____%

[1] Calibration gas concentration - measurement system reading

[2] Absolute value

Figure 2-2. Calibration Error Determination

Test No.	Date and Time	Reference Method Samples					Analyzer 1-Hour Average (ppm)*		Difference (ppm)	
		SO_2 Sample 1 (ppm)	NO_x Sample 1 (ppm)	NO_x Sample 2 (ppm)	NO_x Sample 3 (ppm)	NO_x Sample Average (ppm)	SO_2	NO_x	SO_2	NO_x
1										
2										
3										
4										
5										
6										
7										
8										
9										

Mean reference method test value (SO_2) _____

Mean reference method test value (NO_x) _____

Mean of the differences _____

95% Confidence intervals = ± _____ ppm (SO_2) = ± _____ ppm (NO_x)

Accuracies = $\frac{\text{Mean of the differences} + \text{95\% confidence interval}}{\text{Mean reference method value}}$ x 100 = _____% (SO_2) = _____% (NO_x)

* Explain and report method used to determine integrated averages

Figure 2-3. Accuracy Determination (SO_2 and NO_x)

Data Set No.	Time Begin	Time End	Date	Zero Reading	Zero Drift (ΔZero)	Span Reading	Span Drift (ΔSpan)	Calibration Drift (Span- Zero)
1								
2								
3								
4								
5								
6								
7								
8								
9								
10								
11								
12								
13								
14								
15								

Zero Drift = [Mean Zero Drift* _____ + CI (Zero) _____] ÷ [Span] x 100 = _____.

Calibration Drift = [Mean Span Drift* _____ + CI (Span) _____] ÷ [Span] x 100 = _____.

*Absolute Value.

Figure 2-4. Zero and Calibration Drift (2 Hour)

Date and Time	Zero Reading	Zero Drift (ΔZero)	Span Reading (After zero adjustment)	Calibration Drift (ΔSpan)

Zero Drift = [Mean Zero Drift* _______ + C.I. (Zero) _______]

÷ [Instrument Span] x 100 = _________.

Calibration Drift = [Mean Span Drift* _________ + C.I. (Span) _________]

÷ [Instrument Span] x 100 = _________.

* Absolute value

Figure 2-5. Zero and Calibration Drift (24-hour)

Date of Test _____________

Span Gas Concentration _________ppm

Analyzer Span Setting _________ppm

Upscale
1 ________seconds
2 ________seconds
3 ________seconds

Average upscale response ________seconds

Downscale
1 ________seconds
2 ________seconds
3 ________seconds

Average downscale response ______seconds

System average response time (slower time) = _______seconds.

$$\%\text{deviation from slower system average response} = \left[\frac{\text{average upscale minus average downscale}}{\text{slower time}}\right] \times 100\% = \_\_\_\_.$$

Figure 2-6. Response Time

Performance Specification 3—Performance specifications and specification test procedures for monitors of CO_2 and O_2 from stationary sources.

1. Principle and Applicability.

1.1 Principle. Effluent gases are continuously sampled and are analyzed for carbon dioxide or oxygen by a continuous monitoring system. Tests of the system are performed during a minimum operating period to determine zero drift, calibration drift, and response time characteristics.

1.2 Applicability. This performance specification is applicable to evaluation of continuous monitoring systems for measurement of carbon dioxide or oxygen. These specifications contain test procedures, installation requirements, and data computation procedures for evaluating the acceptability of the continuous monitoring systems subject to approval by the Administrator. Sampling may include either extractive or non-extractive (in-situ) procedures.

2. Apparatus.

2.1 Continuous Monitoring System for Carbon Dioxide or Oxygen.

2.2 Calibration Gas Mixtures. Mixture of known concentrations of carbon dioxide or oxygen in nitrogen or air. Midrange and 90 percent of span carbon dioxide or oxygen concentrations are required. The 90 percent of span gas mixture is to be used to set and check the analyzer span and is referred to as span gas. For oxygen analyzers, if the span is higher than 21 percent O_2, ambient air may be used in place of the 90 percent of span calibration gas mixture. Triplicate analyses of the gas mixture (except ambient air) shall be performed within two weeks prior to use using Reference Method 3 of this part.

2.3 Zero Gas. A gas containing less than 100 ppm of carbon dioxide or oxygen.

2.4 Data Recorder. Analog chart recorder or other suitable device with input voltage range compatible with analyzer system output. The resolution of the recorder's data output shall be sufficient to allow completion of the test procedures within this specification.

3. Definitions.

3.1 Continuous Monitoring System. The total equipment required for the determination of carbon dioxide or oxygen in a given source effluent. The system consists of three major subsystems:

3.1.1 Sampling Interface. That portion of the continuous monitoring system that performs one or more of the following operations: Delineation, acquisition, transportation, and conditioning of a sample of the source effluent or protection of the analyzer from the hostile aspects of the sample or source environment.

3.1.2 Analyzer. That portion of the continuous monitoring system which senses the pollutant gas and generates a signal output that is a function of the pollutant concentration.

3.1.3 Data Recorder. That portion of the continuous monitoring system that provides a permanent record of the output signal in terms of concentration units.

3.2 Span. The value of oxygen or carbon dioxide concentration at which the continuous monitoring system is set that produces the maximum data display output. For the purposes of this method, the span shall be set no less than 1.5 to 2.5 times the normal carbon dioxide or normal oxygen concentration in the stack gas of the affected facility.

3.3 Midrange. The value of oxygen or carbon dioxide concentration that is representative of the normal conditions in the stack gas of the affected facility at typical operating rates.

3.4 Zero Drift. The change in the continuous monitoring system output over a stated period of time of normal continuous operation when the carbon dioxide or oxygen concentration at the time for the measurements is zero.

3.5 Calibration Drift. The change in the continuous monitoring system output over a stated time period of normal continuous operation when the carbon dioxide or oxygen continuous monitoring system is measuring the concentration of span gas.

3.6 Operational Test Period. A minimum period of time over which the continuous monitoring system is expected to operate within certain performance specifications without unscheduled maintenance, repair, or adjustment.

3.7 Response time. The time interval from a step change in concentration at the input to the continuous monitoring system to the time at which 95 percent of the corresponding final value is displayed on the continuous monitoring system data recorder.

4. Installation Specification.

Oxygen or carbon dioxide continuous monitoring systems shall be installed at a location where measurements are directly representative of the total effluent from the affected facility or representative of the same effluent sampled by a SO_2 or NO_x continuous monitoring system. This requirement shall be complied with by use of applicable requirements in Performance Specification 2 of this appendix as follows:

4.1 Installation of Oxygen or Carbon Dioxide Continuous Monitoring Systems Not Used to Convert Pollutant Data. A sampling location shall be selected in accordance with the procedures under paragraphs 4.2.1 or 4.2.2, or Performance Specification 2 of this appendix.

4.2 Installation of Oxygen or Carbon Dioxide Continuous Monitoring Systems Used to Convert Pollutant Continuous Monitoring System Data to Units of Applicable Standards. The diluent continuous monitoring system (oxygen or carbon dioxide) shall be installed at a sampling location where measurements that can be made are representative of the effluent gases sampled by the pollutant continuous monitoring system(s). Conformance with this requirement may be accomplished in any of the following ways:

4.2.1 The sampling location for the diluent system shall be near the sampling location for the pollutant continuous monitoring system such that the same approximate point(s) (extractive systems) or path (in-situ systems) in the cross section is sampled or viewed.

4.2.2 The diluent and pollutant continuous monitoring systems may be installed at different locations if the effluent gases at both sampling locations are nonstratified as determined under paragraphs 4.1 or 4.3, Performance Specification 2 of this appendix and there is no in-leakage occurring between the two sampling locations. If the effluent gases are stratified at either location, the procedures under paragraph 4.2.2, Performance Specification 2 of this appendix shall be used for installing continuous monitoring systems at that location.

5. Continuous Monitoring System Performance Specifications.

The continuous monitoring system shall meet the performance specifications in Table 3-1 to be considered acceptable under this method.

6. Performance Specification Test Procedures.

The following test procedures shall be used to determine conformance with the requirements of paragraph 4. Due to the wide variation existing in analyzer designs and principles of operation, these procedures are not applicable to all analyzers. Where this occurs, alternative procedures, subject to the approval of the Administrator, may be employed. Any such alternative procedures must fulfill the same purposes (verify response, drift, and accuracy) as the following procedures, and must clearly demonstrate conformance with specifications in Table 3-1.

6.1 Calibration Check. Establish a calibration curve for the continuous monitoring system using zero, midrange, and span concentration gas mixtures. Verify that the resultant curve of analyzer reading compared with the calibration gas value is consistent with the expected response curve as described by the analyzer manufacturer. If the expected response curve is not produced, additional calibration gas measurements shall be made, or additional steps undertaken to verify the accuracy of the response curve of the analyzer.

6.2 Field Test for Zero Drift and Calibration Drift. Install and operate the continuous monitoring system in accordance with the manufacturer's written instructions and drawings as follows:

TABLE 3-1.—*Performance specifications*

Parameter	*Specification*
1. Zero drift (2 h) [1]	≤0.4 pct O_2 or CO_2.
2. Zero drift (24 h) [1]	≤0.5 pct O_2 or CO_2.
3. Calibration drift (2 h) [1]	≤0.4 pct O_2 or CO_2.
4. Calibration drift (24 h) [1]	≤0.5 pct O_2 or CO_2.
5. Operational period	168 h minimum.
6. Response time	10 min.

[1] Expressed as sum of absolute mean value plus 95 pct confidence interval of a series of tests.

6.2.1 Conditioning Period. Offset the zero setting at least 10 percent of span so that negative zero drift may be quantified. Operate the continuous monitoring system for an initial 168-hour conditioning period in a normal operational manner.

6.2.2. Operational Test Period. Operate the continuous monitoring system for an additional 168-hour period maintaining the zero offset. The system shall monitor the source effluent at all times except when being zeroed, calibrated, or backpurged.

6.2.3 Field Test for Zero Drift and Calibration Drift. Determine the values given by zero and midrange gas concentrations at two-hour intervals until 15 sets of data are obtained. For non-extractive continuous monitoring systems, determine the zero value given by a mechanically produced zero condition or by computing the zero value from upscale measurements using calibrated gas cells certified by the manufacturer. The midrange checks shall be performed by using certified calibration gas cells functionally equivalent to less than 50 percent of span. Record these readings on the example sheet shown in Figure 3-1. These two-hour periods need not be consecutive but may not overlap. In-situ CO_2 or O_2 analyzers which cannot be fitted with a calibration gas cell may be calibrated by alternative procedures acceptable to the Administrator. Zero and calibration corrections and adjustments are allowed only at 24-hour intervals or at such shorter intervals as the manufacturer's written instructions specify. Automatic corrections made by the continuous monitoring system without operator intervention or initiation are allowable at any time. During the entire 168-hour test period, record the values given by zero and span gas concentrations before and after adjustment at 24-hour intervals in the example sheet shown in Figure 3-2.

6.3 Field Test for Response Time.

6.3.1 Scope of Test.

This test shall be accomplished using the continuous monitoring system as installed, including sample transport lines if used. Flow rates, line diameters, pumping rates, pressures (do not allow the pressurized calibration gas to change the normal operating pressure in the sample line), etc., shall be at the nominal values for normal operation as specified in the manufacturer's written instructions. If the analyzer is used to sample more than one source (stack), this test shall be repeated for each sampling point.

6.3.2 Response Time Test Procedure.

Introduce zero gas into the continuous monitoring system sampling interface or as close to the sampling interface as possible. When the system output reading has stabilized, switch quickly to a known concentration of gas at 90 percent of span. Record the time from concentration switching to 95 percent of final stable response. After the system response has stabilized at the upper level, switch quickly to a zero gas. Record the time from concentration switching to 95 percent of final stable response. Alternatively, for nonextractive continuous monitoring systems, the highest available calibration gas concentration shall be switched into and out of the sample path and response times recorded. Perform this test sequence three (3) times. For each test, record the results on the data sheet shown in Figure 3-3.

7. Calculations, Data Analysis, and Reporting.

7.1 Procedure for determination of mean values and confidence intervals.

7.1.1 The mean value of a data set is calculated according to equation 3-1.

$$\bar{x}=\frac{1}{n}\sum_{i=1}^{n}x_i \qquad \text{Equation 3-1}$$

where:

x_i = absolute value of the measurements,
Σ = sum of the individual values,
$\bar{x}$ = mean value, and
n = number of data points.

7.2.1 The 95 percent confidence interval (two-sided) is calculated according to equation 3-2:

$$\text{C.I.}_{95}=\frac{t_{.975}}{n\sqrt{n-1}}\sqrt{n(\Sigma x_i^2)-(\Sigma x_i)^2} \qquad \text{Equation 3-2}$$

where:

ΣX = sum of all data points,
$t_{.975}$ = $t_1-\alpha/2$, and
C.I._{95} = 95 percent confidence interval estimates of the average mean value.

Values for $t_{.975}$

n	
2	$t_{.975}$
3	12.706
4	4.303
5	3.182
6	2.776
7	2.571
8	2.447
9	2.365
10	2.306
11	2.262
12	2.228
13	2.201
14	2.179
15	2.160
16	2.145
	2.131

The values in this table are already corrected for n-1 degrees of freedom. Use n equal to the number of samples as data points.

7.2 Data Analysis and Reporting.

7.2.1 Zero Drift (2-hour). Using the zero concentration values measured each two hours during the field test, calculate the differences between the consecutive two-hour readings expressed in ppm. Calculate the mean difference and the confidence interval using equations 3-1 and 3-2. Record the sum of the absolute mean value and the confidence interval on the data sheet shown in Figure 3-1.

7.2.2 Zero Drift (24-hour). Using the zero concentration values measured every 24 hours during the field test, calculate the differences between the zero point after zero adjustment and the zero value 24 hours later just prior to zero adjustment. Calculate the mean value of these points and the confidence interval using equations 3-1 and 3-2. Record the zero drift (the sum of the absolute mean and confidence interval) on the data sheet shown in Figure 3-2.

7.2.3 Calibration Drift (2-hour). Using the calibration values obtained at two-hour intervals during the field test, calculate the differences between consecutive two-hour readings expressed as ppm. These values should be corrected for the corresponding zero drift during that two-hour period. Calculate the mean and confidence interval of these corrected difference values using equations 3-1 and 3-2. Do not use the differences between non-consecutive readings. Record the sum of the absolute mean and confidence interval upon the data sheet shown in Figure 3-1.

7.2.4 Calibration Drift (24-hour). Using the calibration values measured every 24 hours during the field test, calculate the differences between the calibration concentration reading after zero and calibration adjustment and the calibration concentration reading 24 hours later after zero adjustment but before calibration adjustment. Calculate the mean value of these differences and the confidence interval using equations 3-1 and 3-2. Record the sum of the absolute mean and confidence interval on the data sheet shown in Figure 3-2.

7.2.5 Operational Test Period. During the 168-hour performance and operational test period, the continuous monitoring system shall not receive any corrective maintenance, repair, replacement, or adjustment other than that clearly specified as required in the manufacturer's written operation and maintenance manuals as routine and expected during a one-week period. If the continuous monitoring system operates within the specified performance parameters and does not require corrective maintenance, repair, replacement or adjustment other than as specified above during the 168-hour test period, the operational period will be successfully concluded. Failure of the continuous monitoring system to meet this requirement shall call for a repetition of the 168 hour test period. Portions of the test which were satisfactorily completed need not be repeated. Failure to meet any performance specifications shall call for a repetition of the one-week performance test period and that portion of the testing which is related to the failed specification. All maintenance and adjustments required shall be recorded. Output readings shall be recorded before and after all adjustments.

7.2.6 Response Time. Using the data developed under paragraph 5.3, calculate the time interval from concentration switching to 95 percent to the final stable value for all upscale and downscale tests. Report the mean of the three upscale test times and the mean of the three downscale test times. The two average times should not differ by more than 15 percent of the slower time. Report the slower time as the system response time. Record the results on Figure 3-3.

8. References.

8.1 "Performance Specifications for Stationary Source Monitoring Systems for Gases and Visible Emissions," Environmental Protection Agency, Research Triangle Park, N.C., EPA-650/2-74-013, January 1974.

8.2 "Experimental Statistics," Department of Commerce, National Bureau of Standards Handbook 91, 1963, pp. 3-31, paragraphs 3-3.1.4.

Data Set No.	Time		Date	Zero Reading	Zero Drift (ΔZero)	Span Reading	Span Drift (ΔSpan)	Calibration Drift (ΔSpan-ΔZero)
	Begin	End						
1								
2								
3								
4								
5								
6								
7								
8								
9								
10								
11								
12								
13								
14								
15								

Zero Drift = [Mean Zero Drift* ______ + CI (Zero) ______] = ______.

Calibration Drift = [Mean Span Drift* ______ + CI (Span ______] = ______.

*Absolute Value.

Figure 3-1. Zero and Calibration Drift (2 Hour).

Date and Time	Zero Reading	Zero Drift (ΔZero)	Span Reading (After zero adjustment)	Calibration Drift (ΔSpan)

Zero Drift = [Mean Zero Drift* ______ + C.I. (Zero) ______]

= ______.

Calibration Drift = [Mean Span Drift* ______ + C.I. (Span) ______]

= ______.

* Absolute value

Figure 3-2. Zero and Calibration Drift (24-hour)

Date of Test ______

Span Gas Concentration ______ ppm

Analyzer Span Setting ______ ppm

Upscale
1. ______ seconds
2. ______ seconds
3. ______ seconds

Average upscale response ______ seconds

Downscale
1. ______ seconds
2. ______ seconds
3. ______ seconds

Average downscale response ______ seconds

System average response time (slower time) = ______ seconds

% deviation from slower system average response = $\frac{\text{average upscale minus average downscale}}{\text{slower time}} \times 100\%$

= ______.

Figure 3-3. Response

[40 FR 46259, Oct. 6, 1975; 40 FR 59204, 59205, Dec. 22, 1975, as amended at 42 FR 5937, Jan. 31, 1977]

APPENDIX E

CONVERSION FACTORS AND USEFUL INFORMATION

E.1 International Metric System – Le Systeme International d'Unites (SI Units)

Base Units of the International Metric System (SI)

Quantity	Name of the Unit	Symbol
Length	meter	m
Mass	kilogram	kg
Time	second	s
Temperature	Kelvin	K
Electric current	ampere	A
Luminous intensity	candela	cd
Amount of substance	mole	mol

E.2 Recommended Decimal Multiples and Submultiples and the Corresponding Prefixes and Names

Factor	Prefix	Symbol	Meaning
10^{12}	tera	T	One trillion times
10^{9}	giga	G	One billion times
10^{6}	mega	M	One million times
10^{3}	kilo	k	One thousand times
10^{2}	hecto	h	One hundred times
10	deca	da	Ten times
10^{-1}	deci	d	One tenth of
10^{-2}	centi	c	One hundredth of
10^{-3}	milli	m	One thousandth of
10^{-6}	micro	μ	One millionth of
10^{-9}	nano	n	One billionth of
10^{-12}	pico	p	One trillionth of
10^{-15}	femto	f	One quadrillionth of
10^{-18}	atto	a	One quintillionth of

E.3 Some Derived Units of the International Metric System (SI)

Quantity	Name of the Unit	Symbol	Equivalence
Frequency	hertz	Hz	$1\ \mathrm{Hz} = 1\ \mathrm{s}^{-1}$
Force	newton	N	$1\ \mathrm{N} = 1\ \mathrm{kg} \times \mathrm{m} \times \mathrm{s}^{-2}$
Pressure	pascal	Pa	$1\ \mathrm{Pa} = 1\ \mathrm{N} \times \mathrm{m}^{-2}$
Energy	joule	J	$1\ \mathrm{J} = 1\ \mathrm{N} \times \mathrm{m}$
Power	watt	W	$1\ \mathrm{W} = 1\ \mathrm{J} \times \mathrm{s}^{-1}$
Quantity of electricity	coulomb	C	$1\ \mathrm{C} = 1\ \mathrm{A} \times \mathrm{s}$
Electrical potential or electromotive force	volt	V	$1\ \mathrm{V} = 1\ \mathrm{W} \times \mathrm{A}^{-1}$
Electric resistance	ohm	Ω	$1\ \Omega = 1\ \mathrm{V} \times \mathrm{A}^{-1}$
Electric conductance	siemens	S	$1\ \mathrm{S} = 1\ \Omega^{-1}$
Electric capacitance	farad	F	$1\ \mathrm{F} = 1\ \mathrm{C} \times \mathrm{V}^{-1}$
Magnetic flux	weber	Wb	$1\ \mathrm{Wb} = 1\ \mathrm{V} \times \mathrm{s}$
Magnetic flux density	tesla	T	$1\ \mathrm{T} = 1\ \mathrm{Wb} \times \mathrm{m}^{-2}$
Inductance	henry	Π	$1\ \Pi = 1\ \mathrm{Wb} \times \mathrm{A}^{-1}$
Luminous flux	lumen	lm	$1\ \mathrm{lm} = 1\ \mathrm{cd} \times \mathrm{sr}$
Illumination	lux	lx	$1\ \mathrm{lx} = 1\ \mathrm{lx} \times \mathrm{m}^{-2}$
Wave number		υ	

E.4 Some Suggested SI Units for Air Pollution Control

Volume flow: Litres per second (l/s)

Velocity (gas flow): Meters per second (m/s)

Air to cloth ratio: Millimeters per second (mm/s)

Pressure: Kilopascals (kPa)

E.5 Conversion from ppm to g/m^3 at STP

$$T_{std} = 273.15°K$$

$$P_{std} = 1\ \text{atm}$$

$$\frac{g}{dscm} = \frac{ppm \times M.W.\left(\frac{g}{g\text{-mole}}\right)}{22.414\ \frac{\text{liters}}{g\text{-mole}} \times 10^{-3}\ \frac{m^3}{10^3 l}\left(\frac{293.15°K}{273.15°K}\right)} \times \frac{1}{1 \times 10^6\ ppm}$$

E.6 Conversion Factors

Equivalents	Multiply	by	to obtain
Energy, Heat, and Work:			
1 Btu = 252.0 cal	Btu	252.0	cal
	cal	0.003968	Btu
1 Btu = 0.2520 kg-cal	Btu	0.2520	kg-cal
	kg-cal	3.968	Btu
1 therm = 100,000 Btu	therm	100,000	Btu
	Btu	0.00001	therm
1 Btu = 778.2 ft-lb	Btu	778.2	ft-lb
	ft-lb	0.001285	Btu
1 Btu = 1055 Joules	Btu	1055	Joules
	Joules	0.0009478	Btu
1 cal = 4.187 Joules	cal	4.187	Joules
	Joules	0.2388	cal
1 hp-hr = 2544 Btu	hp-hr	2544	Btu
	Btu	0.0003930	hp-hr
1 kwh = 3412 Btu	kwh	3412	Btu
	Btu	0.0002931	kwh
1 hp-hr = 1,980,000 ft-lb	hp-hr	1,980,000	ft-lb
	ft-lb	0.0000005051	hp-hr
1 kg-m = 7.233 ft-lb	kg-m	7.233	ft-lb
	ft-lb	0.1383	kg-m
Power and Heat Flow:			
1 kw = 1.341 hp	kw	1.341	hp
	hp	0.7457	kw
1 hp = 550 ft-lb/sec	hp	550	ft-lb/sec
	ft-lb/sec	0.001818	hp
1 hp = 42.41 Btu/min	hp	42.41	Btu/min
	Btu/min	0.02358	hp
1 Btu/sec = 1.055 kw	Btu/sec	1.055	kw
	kw	0.9478	Btu/sec
1 kw = 3412 Btu/hr	kw	3412	Btu/hr
	Btu/hr	0.0002931	kw
1 hp = 2544 Btu/hr	hp	2544	Btu/hr
	Btu/hr	0.0003930	hp
	Btu/min	0.01757	kw
	kw	56.92	Btu/min
	Btu/min	0.001	lb/hr (steam)
	lb/hr steam	0.454	kg/hr (steam)
	Mega watts	1360	kg/hr (steam)
	Boiler Hp	33,479	Btu/hr
	Boiler Hp	9,803	kw

Equivalents	Multiply	by	to obtain
Heat Flux:			
1 cal/hr sq cm = 3.687 Btu/hr sq ft	cal/hr sq cm	3.687	Btu/hr sq ft
	Btu/hr sq ft	0.2712	cal/hr sq cm
1 watt/sq cm = 3170 Btu/hr sq ft	watts/sq cm	3170	Btu/hr sq ft
	Btu/hr sq ft	0.0003154	watts/sq cm
Thermal Conductivity:			
$1\,\frac{\text{Btu ft}}{\text{hr sq ft °F}} = 12\,\frac{\text{Btu in.}}{\text{hr sq ft °F}}$	$\frac{\text{Btu ft}}{\text{hr sq ft °F}}$	12	$\frac{\text{Btu in.}}{\text{hr sq ft °F}}$
	$\frac{\text{Btu in.}}{\text{hr sq ft °F}}$	0.0833	$\frac{\text{Btu ft}}{\text{hr sq ft °F}}$
$1\,\frac{\text{Btu ft}}{\text{hr sq ft °F}} = 14.88\,\frac{\text{cal cm}}{\text{hr sq cm °C}}$	$\frac{\text{Btu ft}}{\text{hr sq ft °F}}$	14.88	$\frac{\text{cal cm}}{\text{hr sq cm °C}}$
	$\frac{\text{cal cm}}{\text{hr sq cm °C}}$	0.0672	$\frac{\text{Btu ft}}{\text{hr sq ft °F}}$
$1\,\frac{\text{watt cm}}{\text{sq cm °C}} = 57.79\,\frac{\text{Btu ft}}{\text{hr sq ft °F}}$	$\frac{\text{watts cm}}{\text{sq cm °C}}$	57.79	$\frac{\text{Btu ft}}{\text{hr sq ft °F}}$
	$\frac{\text{Btu ft}}{\text{hr sq ft °F}}$	0.01731	$\frac{\text{watts cm}}{\text{sq cm °C}}$
Heat Content:			
$1\,\frac{\text{Btu}}{\text{lb}} = 0.556\,\frac{\text{cal}}{\text{gm}}$	heat content in Btu/lb	0.556	heat content in cal/gm
	heat content in cal/gm	1.80	heat content in Btu/lb
$1\,\frac{\text{Btu}}{\text{lb °F}} = 1\,\frac{\text{cal}}{\text{gm °C}}$	specific heat in Btu/lb °F	1	specific heat cal gm °C

E.7 Conversion Between Different Units

We have gathered below quantities of the English and engineering systems of units that are commonly found in the literature on air pollution. Our intention is to list them in such a way that their equivalent in the MKS system of units can be found quickly. Quantities which are listed in each horizontal line are equivalent. The quantity in the middle column indicates the simplest definition or a useful equivalent of the respective quantity in the first column.

1 acre	$1/640$ mi^2	4.047×10^3 m^2
1 Angstrom (Å)	10^{-8} cm	10^{-10} m
1 atmosphere (atm)	1.013×10^6 dyn/cm^2	1.013×10^5 N/m^2
1 bar (b)	10^6 dyn/cm^2	10^5 N/m^2
1 barrel (bbl)	42 gal, U.S.A.	0.159 m^3
1 boiler horsepower	3.35×10^4 Btu/hr	9.810×10^3 W
1 British Thermal Unit (Btu)	252 cal	1.054×10^3 J
1 Btu/hour	1.93×10^6 erg/sec	0.293 W
1 calorie (cal)	4.184×10^{-7} erg	4.184 J
1 centimeter of mercury (cm Hg)	1.333×10^4 dyn/cm^2	1.333×10^3 N/m^2
1 cubic foot, U.S.A. (cu ft)	2.832×10^4 cm^3	2.832×10^{-2} m^3
1 dyne (dyn)	1 g-cm/sec^2	10^{-5} N
1 erg	1 g-cm^2/sec^2	10^{-7} J
1 foot, U.S.A. (ft)	30.48 cm	0.3048 m
1 foot per minute (ft/min)	1.829×10^{-2} km/hr	5.080×10^{-3} m/sec
1 gallon, U.S.A. (gal)	3.785×10^3 cm^3	3.785×10^{-3} m^3

E.8 Pressure

To / From	mmHg	in Hg	in H_2O	ft H_2O	atm	lb/in^2	Kg/cm^2
mm Hg	1	0.03937	0.5353	0.04460	0.00132	0.01934	0.00136
in Hg	25.40	1	13.60	1.133	0.03342	0.4912	0.03453
in H_2O	1.868	0.07355	1	0.08333	0.00246	0.03613	0.00254
ft H_2O	22.42	0.8826	12	1	0.02950	0.4335	0.03048
atm	760	29.92	406.8	33.90	1	14.70	1.033
lb/in^2	51.71	2.036	27.67	2.307	0.06805	1	0.07031
Kg/cm^2	735.6	28.96	393.7	32.81	0.9678	14.22	1

E.9 Volume

To / From	cm^3	liter	m^3	in^3	ft^3
cm^3	1	0.001	1×10^{-6}	0.06102	3.53×10^{-5}
liter	1000	1	0.001	61.02	0.03532
m^3	1×10^{-6}	1000	1	6.10×10^{-4}	35.31
in^3	16.39	0.01639	1.64×10^{-6}	1	5.79×10^{-4}
ft^3	2.83×10^{-4}	28.32	0.02832	1728	1

E.10 Temperature

$°C = 5/9\ (°F-32)$	$°F = 9/5\ °C+32$
$°K = °C+273.2$	$°R = °F+459.7$

E.11 Conversions – Dust Loadings in Flue Gas (Approximate)

Grains per standard cubic foot	× 1.87	= lbs. per 1000 lbs. of flue gas
Grains per standard cubic foot	× 2.20	= lbs. per 1,000,000 Btu input
Grains per cubic foot of 500° F flue gas	× 3.45	= lbs. per 1000 lbs. of flue gas
Pounds per 1000 lbs. of flue gas	× 0.53	= grains per standard cubic foot
Pounds per 1000 lbs. of flue gas	× 0.29	= grains per cubic foot of 500° F flue gas
Pounds per 1000 lbs. of flue gas	× 1.18	= lbs. per 1,000,000 Btu input
Pounds per 1,000,000 Btu input	× 0.45	= grains per standard cubic foot
Pounds per 1,000,000 Btu input	× 0.85	= lbs. per 1000 lbs. of flue gas
Pounds per 100 lbs. of Type 0 Waste	× 1.01	= lbs. per 1000 lbs. of flue gas
Pounds per 100 lbs. of Type 1 Waste	× 1.30	= lbs. per 1000 lbs. of flue gas
Pounds per 100 lbs. of Type 2 Waste	× 1.84	= lbs. per 1000 lbs. of flue gas
Pounds per 100 lbs. of Type 3 Waste	× 2.80	= lbs. per 1000 lbs. of flue gas
Pounds per 100 lbs. of Type 0 Waste	× 0.54	= grains per standard cubic foot
Pounds per 100 lbs. of Type 1 Waste	× 0.70	= grains per standard cubic foot
Pounds per 100 lbs. of Type 2 Waste	× 0.90	= grains per standard cubic foot
Pounds per 100 lbs. of Type 3 Waste	× 1.50	= grains per standard cubic foot
Pounds of flue gas per hour	× 0.22	= standard cubic feet per minute
Standard cubic feet per minute	× 4.50	= lbs. of flue gas per hour

NOTE:

Grains is a measure of weight; 7000 grains = 1 pound. In these Standards, all expressions of particulate emissions (dust loadings) are given with the total flue gases (products of combustion) corrected to 50 percent excess air.

All factors are based on properties of flue gas approaching those of dry air.

For ease of calculations any small differences are ignored and "corrected to 50 percent excess air" and "corrected to 12 percent CO_2" are considered equal.

Standard cubic feet is air at 70° F, and 29.92 inches of mercury.

E.12 Useful Information

Energy equivalences of various fuels:

Bituminous coal – 22.4 × 10^6 Btu/ton, 1971-1973
– 21.9 × 10^6 Btu/ton, 1974

Anthracite coal – 26.0 × 10^6 Btu/ton

Lignite coal – 16.0 × 10^6 Btu/ton

Residual oil – 147,000 Btu/gal

Distillate oil – 140,000 Btu/gal

Natural gas – 1,022 Btu/ft^3

1 lb. of water evaporated from and at 212°F equals:

0.2844 Kilowatt-hours
0.3814 Horsepower-hours
970.2 Btu

1 cubic foot air weighs 34.11 gm.

Miscellaneous Physical Constants

Avogadro's Number	6.0228 × 10^{23}	Molecules/gm-mole
Gas-Law Constant R	1.987	Cal/(gm-mole) (°K)
	1.987	Btu/(lb-mole) (°R)
	82.06	(cm^3) (atm)/(gm-mole) (°K)
	10.731	(ft^3) (lb) (in^2)/(lb-mole) (°R)
	0.7302	(ft^3) (atm)/(lb-mole) (°R)

Weight of O_2, N_2 and Air

		Pounds	Tons	SCF Gas
1 POUND	Oxygen Nitrogen	1.0	0.0005	12.08 13.80
1 TON	Oxygen Nitrogen	2000.0	1.0	24,160 27,605
1 SCF GAS	Oxygen Nitrogen	0.08281 0.07245	0.00004141 0.00003623	1.0

Air Density = 1.293 g/l at 1 atm 0°C
= 0.0808 lb/ft^3 at atm 32°F

Gram Mole = 22.414 liters at 0°C, 1 atm

1 lb. Mole = 359.05 ft^2 at 32°F, 1 atm

1 Boiler Horsepower:

= 33,475.3 Btu/hr heat to steam

= 34.5 lbs steam evaporated per hr from and at 212°F

= 44,633 Btu/hr fuel input for 75 percent overall efficiency

= approximately 10 sq ft of boiler heating surface (basis for boiler ratings)

= 139.4 sq ft of equivalent direct radiation

Overall Boiler Efficiency, Percent:

$$= \frac{\text{(lb steam/hr)} \times \text{(heat content of delivered steam - heat content of feed water)}}{\text{(fuel input rate)} \times \text{(gross heating value of the fuel)}} \times 100$$

Over-Rate Firing (Common Practice):

Cast iron sectional boilers	125 percent rating
Steel fire tube and brick set horizontal return tube (HRT)	150 percent rating
Scotch marine boilers (conventional type)	200 percent rating
Water tube boilers (small)	300 percent rating
Water tube boilers (large, power type)	600 percent rating

1 Sq Ft of Equivalent Direct Radiation (EDR):

= 240 Btu/hr for steam heating
= 150 Btu/hr for hot water heating (open system)
= 180 Btu/hr for hot water heating (closed system)

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